

5-4-2009

# Solar Cooling Demonstration Unit

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Indiana University - Purdue University Fort Wayne  
Department of Engineering



ENGR 411

Capstone Senior Design Project

Report #2

Project: Solar Cooling Demonstration Unit

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Date: May 4, 2009

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## **Acknowledgement**

The solar cooling demonstration unit project team would like to thank and acknowledge the following individuals and companies for their support and guidance through the design process.

- |                           |                       |
|---------------------------|-----------------------|
| • Dr. Hosni Abu-Mulaweh   | Senior Design Advisor |
| • Dr. Guoping Wang        | Senior Design Advisor |
| • Dr. Donald Mueller, Jr. | Senior Design Advisor |
| • ASHRAE                  | Sponsor               |
| • Shambaugh & Son         | Donator               |
| • Danfoss                 | Donator               |
| • Precision Laser         | Donator               |
| • Wagner-Meinert          | Donator               |

## **Abstract**

Through a grant from the American Society of Heating, Refrigeration, and Air Conditioning Engineers, the Department of Engineering at Indiana-Purdue of Fort Wayne, Indiana has commissioned the design of a solar cooling demonstration unit. The unit is to be based upon and active type solar cooling system. The unit is also to make use of an absorption cycle and a desiccant.

For the detailed mechanical design, an Engineering Equation Solver program was created to model the absorption cycle. Assumptions about the system such as adiabatic expansion valves were made and put into the program. Input variables were then decided upon. The main input variable into the system was the cooling load for the conditioned space. These inputs are used to find the properties at each state and the heat transfer and temperatures needed from the solar collectors. From the solutions of the EES program, components were able to be selected using the state point properties.

For the electrical design, the load from the mechanical design was used to size the battery pack. The solar panels were then sized to meet the battery pack capacity requirements. The current flow from the solar panels to the battery pack was calculated and the regulator was chosen to meet this current rating. The control circuit was the next aspect of the design that was considered. The microcontroller of the system was then chosen to meet the 24 I/O pin requirement and also to meet the current capabilities of the IPFW hardware. This microcontroller will be used to control the solar cooling demonstration unit. The digital temperature sensor was chosen based on its compatibility with the system and availability for simulation on IPFW's software. The user interface was then design to include a LCD module, two momentary push buttons, and two switches.

Building of the unit was done in parts, mechanical and electrical. The mechanical portion was done by fabricating a cart and then mounting the components to the cart. CPVC was used to construct the heat source loop, hot water, while PVC was used to make the cold water loop. 3/8" tubing was used to connect all of the components. Flow meters, thermocouples, and pressure gauges were incorporated into the system to be used for parameter measurements. Plywood and Plexiglas was used to create the 1 meter space to be cooled and 2x4s were used to construct mounts for both the solar collector and solar panel.

The electrical portion was tested throughout the semester. Initially, the Keil software was used to program and simulate a virtual control circuit which was built on the Proteus software. The circuit used a generic AT89C51 microcontroller. The program code was made in Keil and linked to the Proteus software so the system could be simulated. The Silicon Labs IDE software was used to program and test the C8051F930 development board. Portions of the control circuit were programmed and tested on breadboards. Individual components were also tested. After the testing, the development board, the PCB, and two other small circuit boards were connected to the system and enclosed in a metallic box. The user interface was made accessible by integrating the buttons, switches and 7-segment LEDs onto the box.

During testing, it was found that the mechanical system did not function properly. As a result, the mechanical and electrical portions of the project were not tested together. In order to get the unit working properly, the ammonia pump needs to be replaced and the generator needs to be redesigned.

## **Section I: Detailed Design**



## **Mechanical Design**

### **Component Selection**

For the overall system, 3/8" pipe will be used to connect components. Carbon steel seamless tubing will be used due to its compatibility with ammonia. Steel Yor-Lock fittings will be used to connect the components due to the pressure requirements. A Yor-Lock fitting is a threaded fitting on one end and a compression fitting on the other. Water loops are used in two components of the system, the condenser and the absorber heat exchanger. Tap water will be used as for the water loops.

### Desiccant/Refrigerant

Ammonia is to be used as the refrigerant within the system while the water will act as the desiccant. The cooling unit will be charged and pressure tested by Shambaugh & Son. The system will be built in Shambaugh & Son's facilities and testing will be done prior to them releasing the unit for use at IPFW.

The concentrations of the strong absorbent solution were calculated to be 37.93% while the weak absorbent solution was calculated to be 38.91%.

### Solar Collector

A heat transfer of 2.65 kW will be needed in the generator. The incoming temperature from the heat source needs to be 208°F. Due to budget constraints, a SunMaxx flat plate solar collector will be used to start heating the solution. The solution will then pass into a storage tank with a screw plug immersion heater. The heater is a McMaster Carr heater with a thermostat. The heater is a 3,000 Watt, 120 V AC, single phase heater and will heat to 250°F. This tank and heater will be implemented into the solar cooling unit so that it can be easily removed and replaced with solar collectors.

### Generator/Absorber

The generator is designed to run the weak desiccant solution over a series of coils heated by the water from the heat source. The refrigerant then evaporates out of the solution and the solution becomes a strong absorbent solution.

Due to the high pressure needed inside the generator, 7.75 bar, it was decided that a more sturdy design was necessary. Shambaugh & Son has offered to provide an air purger which can function as a tank in which the heat exchange between the desiccant solution and the solar collector can occur.

The coils will use 1/2" (1.27 cm) diameter 304 stainless steel tubing with a .035" (.89 mm) wall thickness. There will be 8.8 coils with a mean diameter of 6.75" (15.88 cm). There will also be a

hollow cylindrical piece of steel 6" (13.34 cm) in diameter which will sit in the middle of the coils to direct the desiccant solution over the hot water coils. This will decrease the area of flow while maintaining the same mass flow rate, thereby increasing the fluid velocity and the convective heat transfer coefficient. A model of the generator design is shown in Figure 1 and Figure 2.

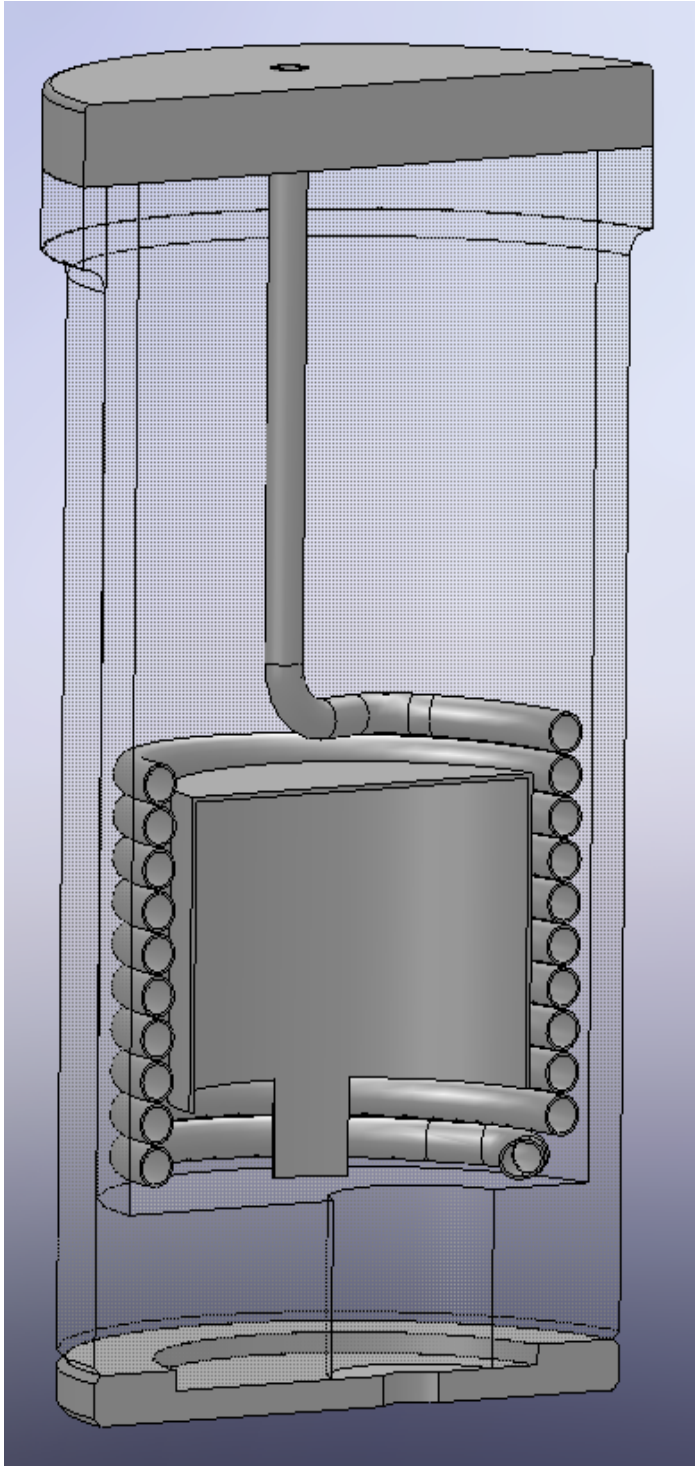


Figure 1: Cutaway View of Generator Design

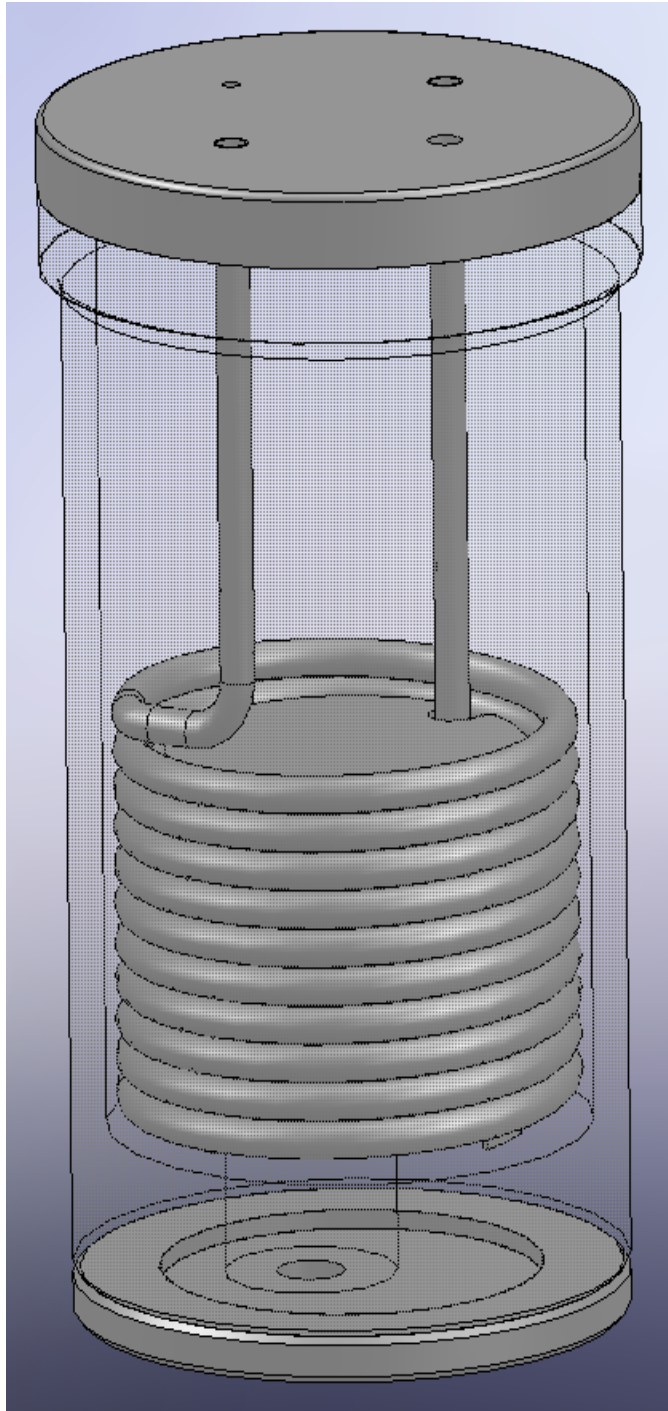


Figure 2: Design of Generator

The absorber is simply a mixing tank. A drawing of the design can be seen in Figure 3. A pressurized tank with connectors for the ammonia from the evaporator and the strong absorbent solution from the generator can be input while an outlet for the newly mixed weak absorbent solution is positioned at the bottom of the tank. Shambaugh & Son have offered to make a tank for us in their fabrication shop.

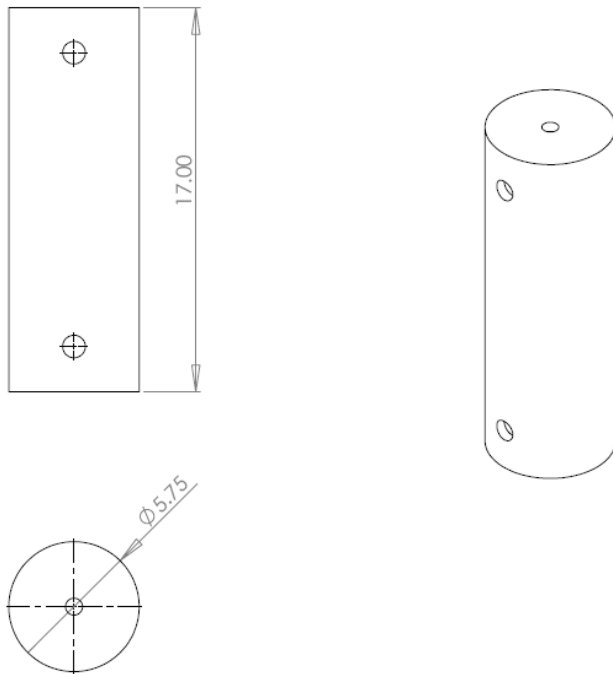


Figure 3: Absorber Design

### Condenser

The heat transfer needed in the condenser is 1.52 kW. A flat plate heat exchanger will be used as the condenser. The ammonia will flow through one side while tap water will be used to condense the ammonia. The heat exchanger is a GEA Flat Plate model number CA1A-UM. A detail of the CA1A-UM condenser is included in Figure 4.

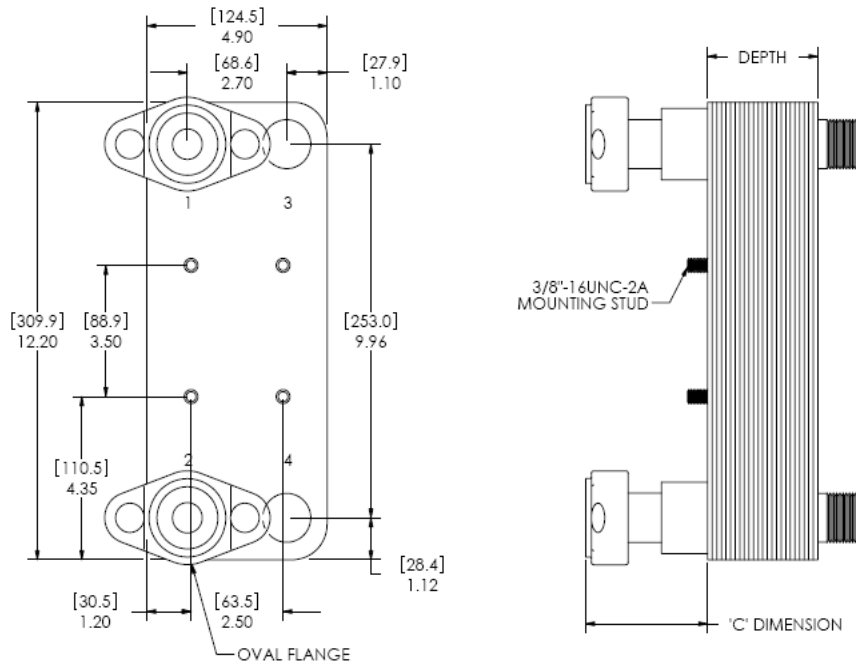


Figure 4: Condenser Detail

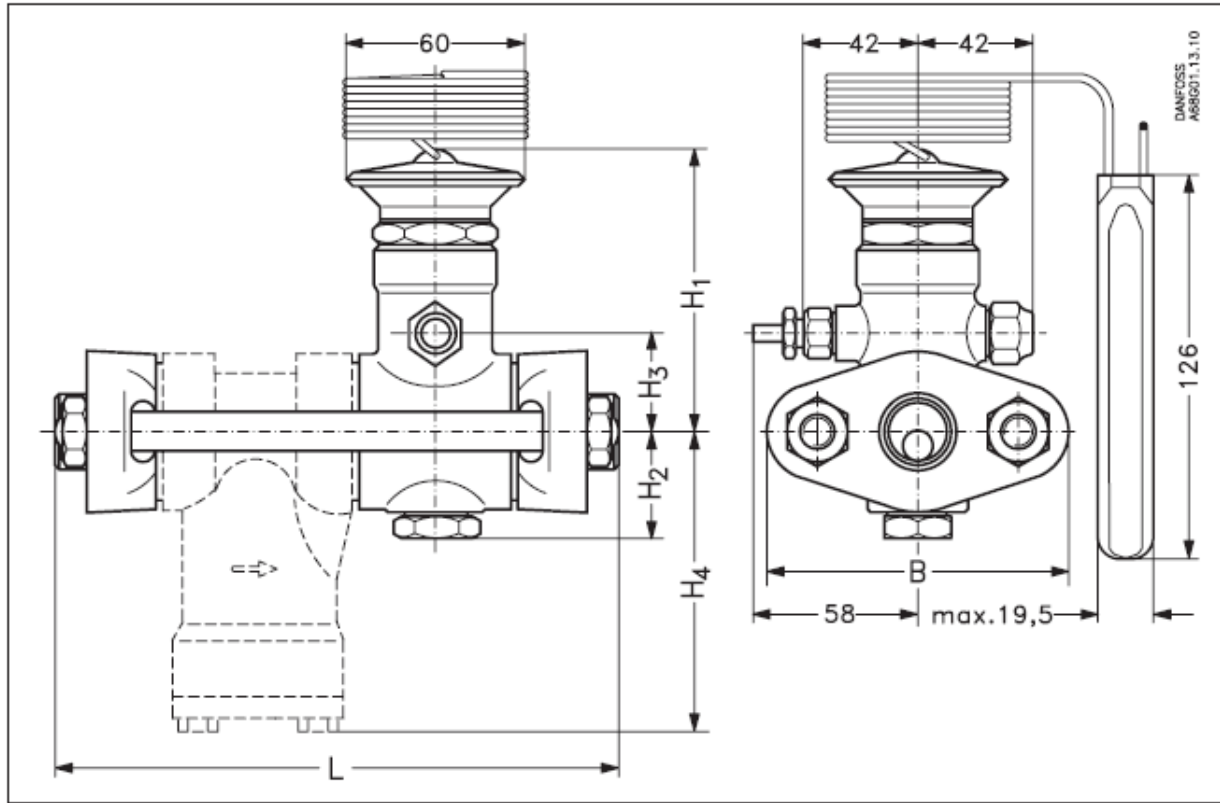
### Evaporator

The evaporator that will be used in the design is a direct expansion evaporator from Super Radiator Coils. The incoming temperature to the evaporator is 46.4°F. Three fans will be used to circulate the cool air into the conditioned space is an Orion DC fan. The fans are 12 V DC fans. The fans supply air at 120 CFM.

### Expansion Valves

Keeping a steady temperature at the outlet of the evaporator would help keep the evaporator from freezing. A thermostatic expansion valve was chosen to be implemented into the design. To avoid freezing the evaporator outlet temperature was chosen to be 8°C and the cooling load was chosen to be 1.5 kW. From these specifications, the thermostatic valve that will be used is the TEA 20-1. A detailed drawing of the TEA 20-1 is shown in Figure 5. This valve provides a 2 bar pressure drop. This valve will be donated by Danfoss.

A second valve is needed between the absorber heat exchanger and the absorber. This valve does not need to be a thermostatic because there are no state points at the absorber that would benefit the system by being held constant. Also a constant pressure was not the best choice in expansion valves for this location in the system either. Instead a hand expansion valve will be used to regulate the pressure drop. This valve will also be donated by Shambaugh & Sons.



Type	$H_1$	$H_2$	$H_3$	$H_4$	L		B	Weight	
					Excl. strainer	Incl. strainer		Excl. strainer	Incl. strainer
	mm	mm	mm	mm	mm	mm	mm	kg	kg
TEA 20	94	38	25	96	110	164	80	2.1	3.0
TEA 85	104	37	35	106	125	199	95	3.0	4.5

Figure 5: Thermostatic Valve Detail

### Absorber Heat Exchanger

The flat plate heat exchanger will cool the strong absorbent solution on its way to the absorber with a water loop. From the inlet and outlet temperatures found in the EES program and the mass flow rate of the strong absorbent solution, GEA Flat Plate's software, GEA FlatPlateSELECT-ONLINE, was able to size a heat exchanger to fit our specifications. The heat exchanger that will be used is the model FPN5x12-4 (1/2" MPT). Figure 6 shows a detailed drawing for the absorber heat exchanger.

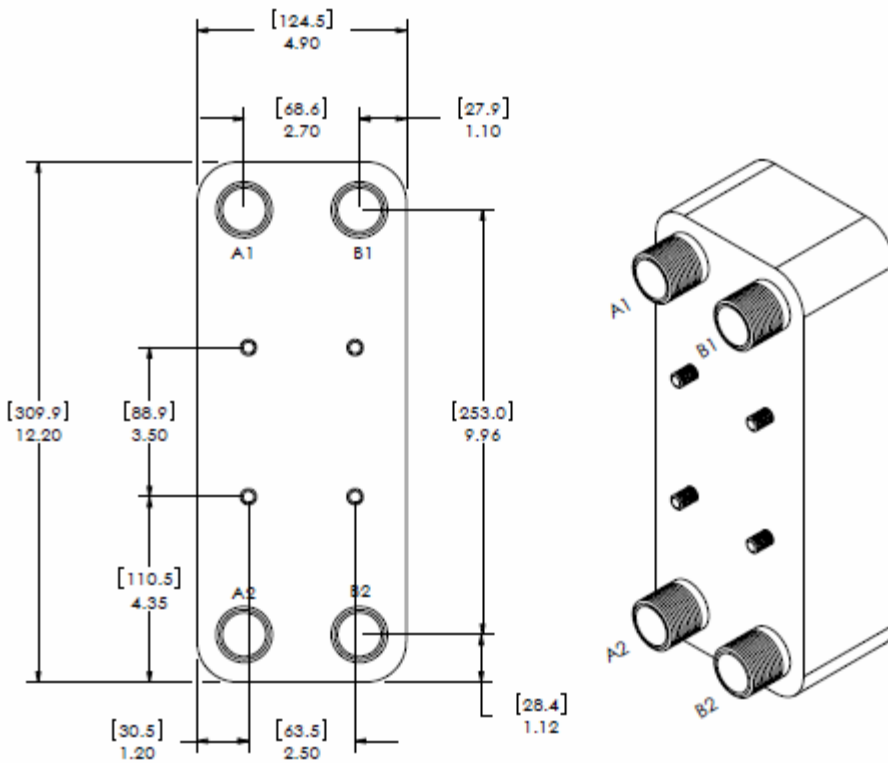


Figure 6: Absorber Heat Exchanger Detail

#### Generator/Absorber Heat Exchanger

The primary concept for the generator/absorber heat exchanger was the flat plate heat exchanger and was also used in the design. This heat exchanger is used to cool the strong absorbent solution that is on its way to the absorber while preheating the weak absorbent solution on its way to the generator. As with the absorber heat exchanger, the inlet and outlet temperatures, the concentrations of the aqueous ammonia solutions, and the mass flow rates of the solutions were input into GEA Flat Plate's software, GEA FlatPlateSELECT-ONLINE, and was able to adequately size a heat exchanger for the cooling unit. The model to be used for the strong absorbent solution to the weak absorbent solution heat exchange is the FPN5x12-8 (1/2" MPT), a detail of this model is shown in Figure 7.

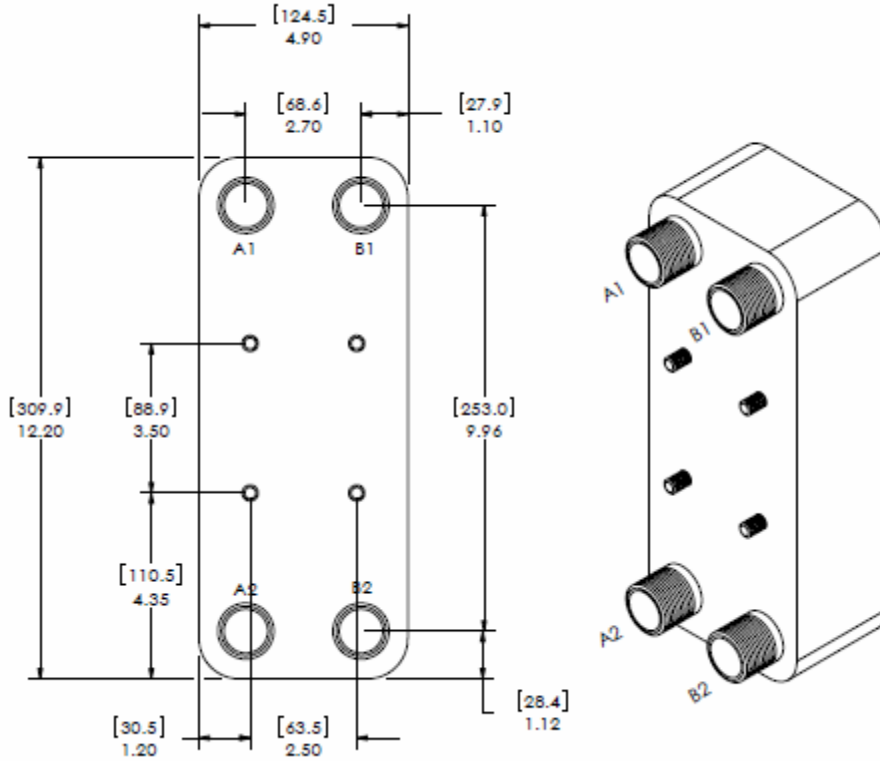


Figure 7: Generator/Absorber Heat Exchanger Detail

### Pumps

To select the pumps, an Excel spreadsheet was made. The inputs to this program were pipe diameter, fluid density, fluid viscosity, cutoff pressure, and maximum flow rate. The relationship between pressure, volume flow rate, maximum pressure, and maximum volume flow rate is shown below.

$$\frac{P}{P_{\max}} = 1 - \left( \frac{V}{V_{\max}} \right)^2 \quad \text{eq. 12}$$

The output of the spreadsheet was a graph of the pump curve found using equation 12 and system curve to find the operating point. This was done for both the generator/absorber pump and the solar collector pump.



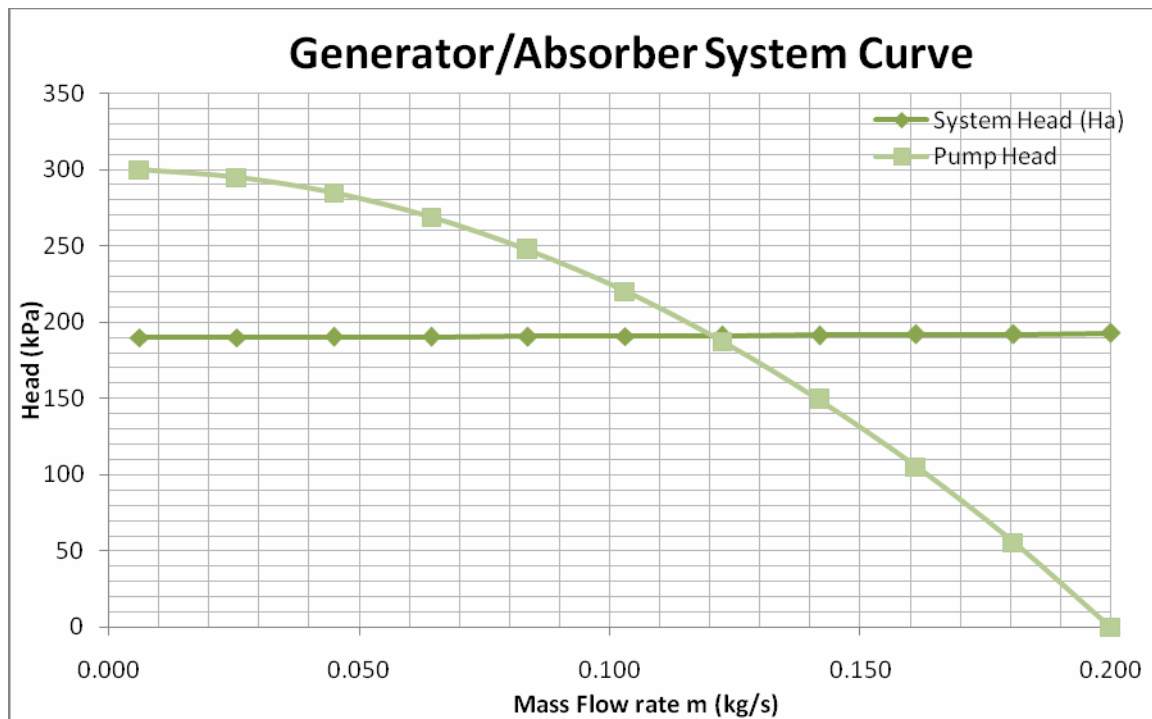


Figure 8: Generator/Absorber System Curve

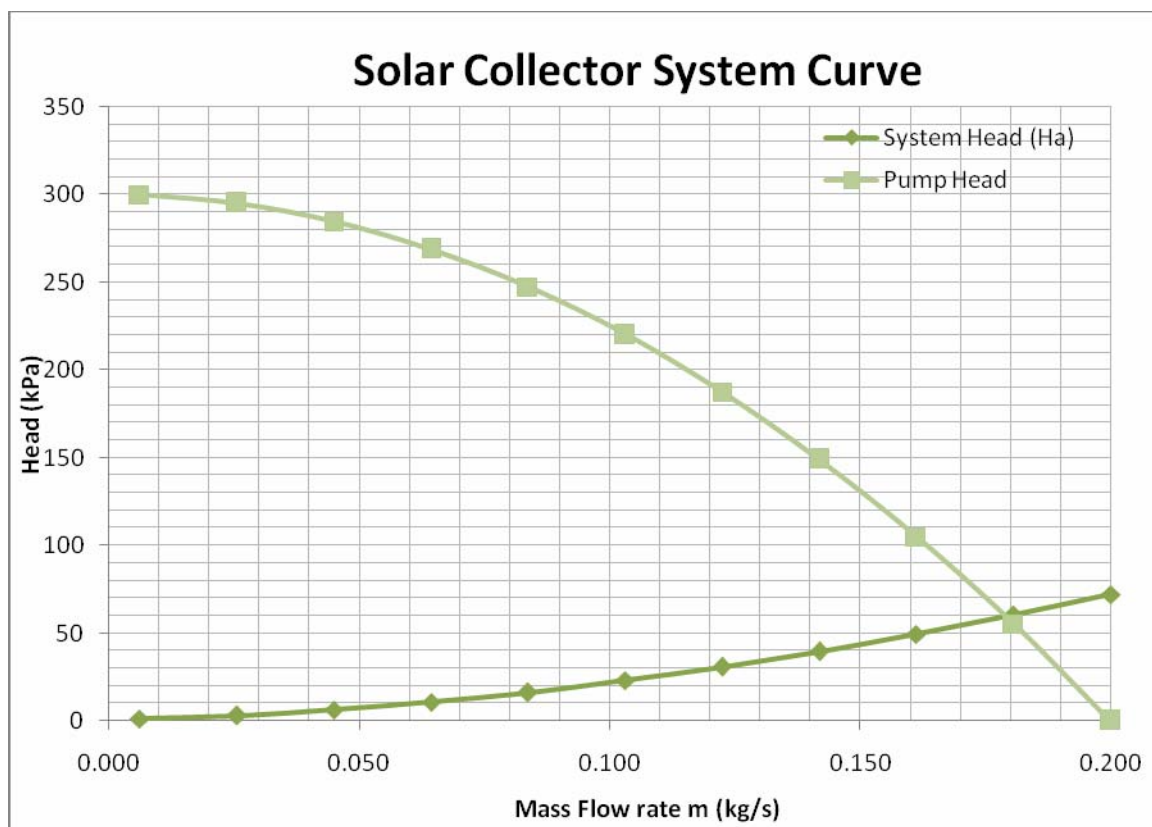


Figure 9: Solar Collector System Curve

The pump used for the heat source loop will be a Whale Universal UF1215. This pump is rated at 12 V DC and 8 Amps. The cutout pressure is 45PSI and the maximum flow rate is 3.2 GPM. The pump used for the remaining system is a SHURflo High Pressure pump. It is rated at 12 V DC, has a 100 psi demand, and has a 1.6 GPM maximum flow rate.

### Cart

A cart will be constructed to house the components of the absorption cycle. The legs of the cart will be constructed from 2.5" square HR A36 tubing and the shelves and brackets will be made from 48x96" 13 ga. HR sheet metal. Wheels obtained from McMaster Carr will be used to make the cart mobile. Two caster swivel will be used on one end of the cart while two rigid caters will be used for wheels on the other end. A 3D model of the cart design is shown in Figure 10. System models can be seen in Figure 11 and Figure 12.

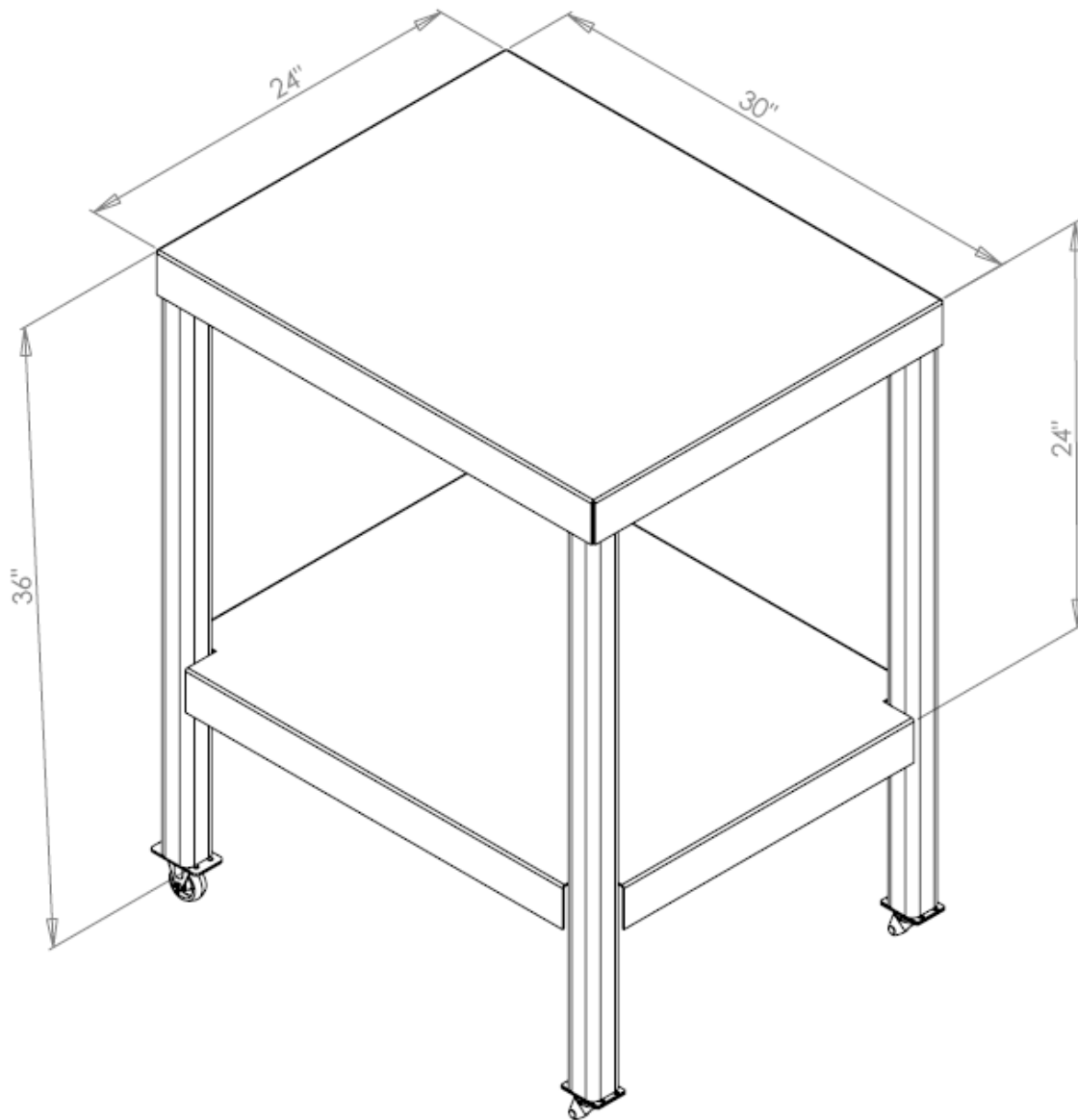


Figure 10: Cart Design

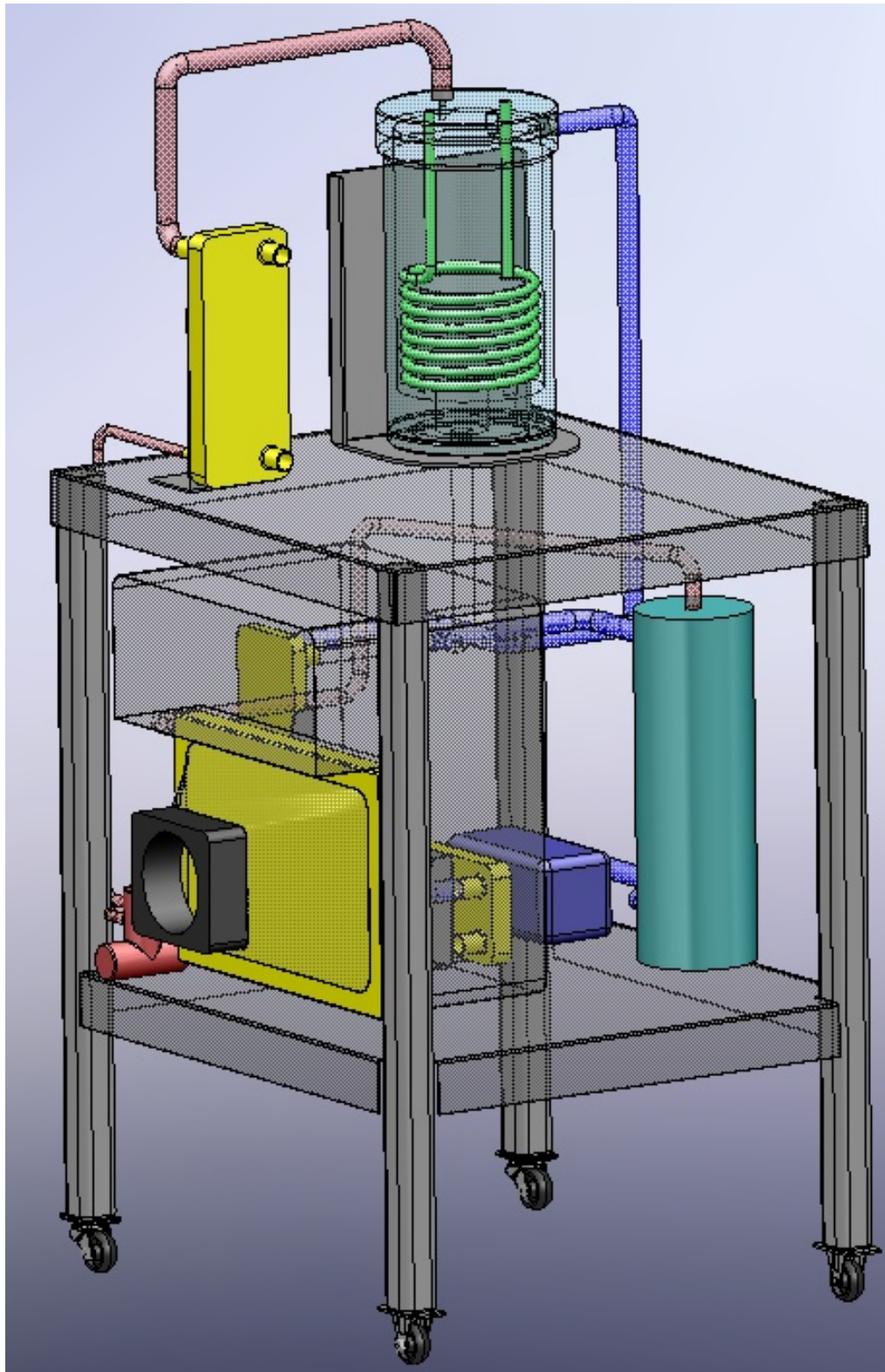


Figure 11: 3D system model

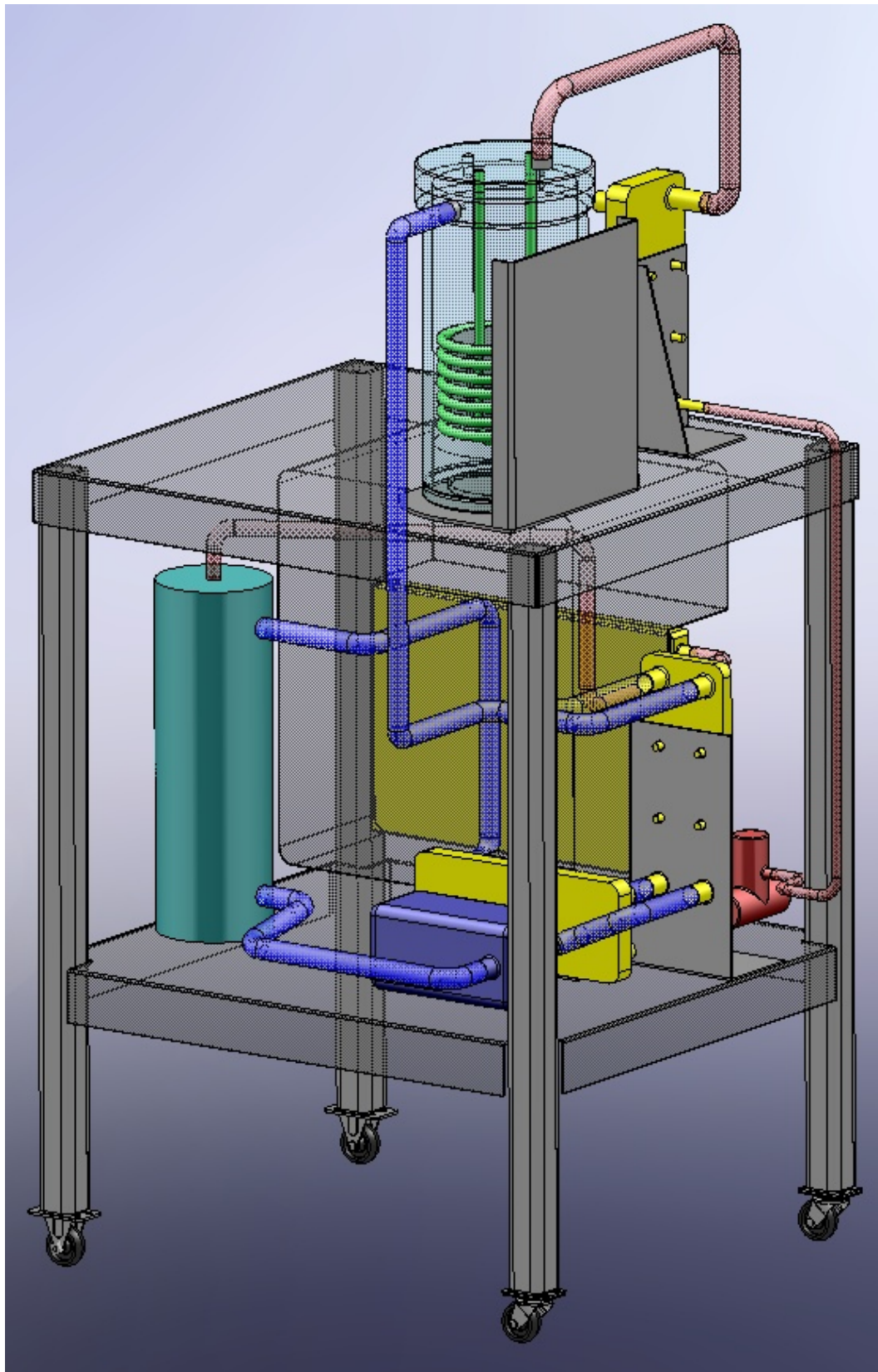


Figure 12: 3D model of system

## Electrical Design

The electrical system provides the power to the mechanical system and also provides control. Figure 13 shows that the electrical system consists of a photovoltaic array, charge controller/regulator, battery pack, DC-DC converter, and a control circuit. In addition to these major components, other components will be used in order to maintain an operational circuit. Each of the major components will be discussed in detail.

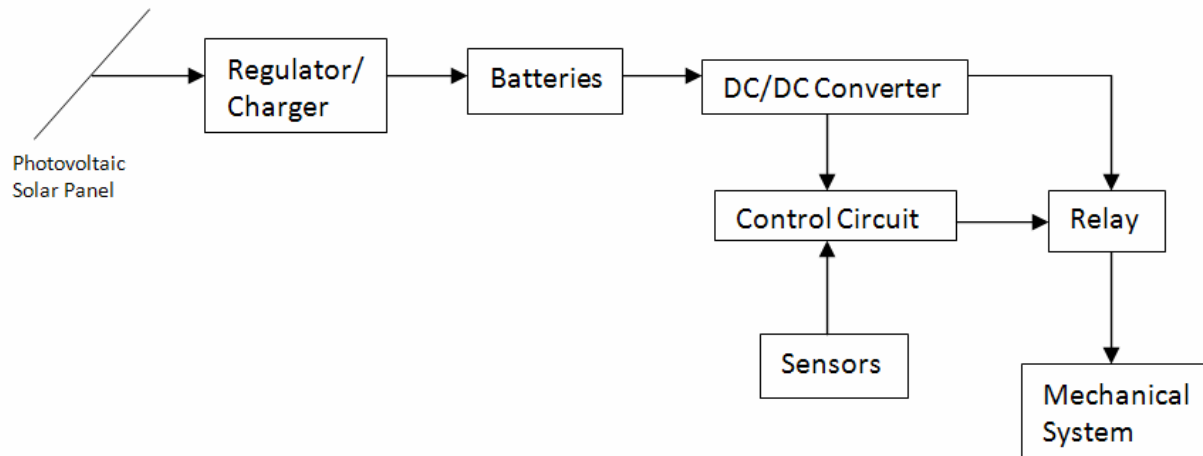


Figure 13: Schematic of Electrical System

### Battery Pack

The battery pack has influence on other components in the system. The size of the battery pack dictates the size of the solar panels, the characteristics of the regulator, and the characteristics of the DC-DC converter. The batteries that are chosen for this design must be able to handle the constant charging from the solar panels and provide enough power to the mechanical system. Based on these criteria, deep cycle lead acid batteries will be the optimal solution and will be used in this design.

The first step towards determining the size of the battery pack is to calculate how much power is required to run the system. The power needed by the system depends primarily on the design of the mechanical system. The mechanical system will include two pumps, a fan, and a solenoid valve, consuming a total of 240 Watts. Therefore, this system needs approximately 240 Watts for 3 to 4 hours as specified in the problem statement. It is also standard practice to introduce a safety factor of about 20 percent to account for losses in the system and to provide a buffer to make sure the system will run for the desired amount of time. Therefore, 240 Watts for 4 hours with a safety factor of 20 percent gives a power of 1152 W·hrs.

To obtain the Amp-hours of the battery pack the amount of power needed must be divided by the voltage of the battery pack. In solar applications, the voltage of the battery pack is typically 12, 24, or 48 volts. This is because most solar panels are made to produce voltages at either 12 or 24 volts. It was decided that this system would use a 12 volt battery pack. Therefore, the battery



pack will need to have the capacity of 96 A·hrs. The battery pack will be made up of 2 deep cycle lead acid batteries in series that have a capacity of at least 96 A·hrs.

### Solar Panels

The solar panels will be used to charge the battery pack. In order to determine the size of the solar panel that is needed, the amount of peak solar radiation for Fort Wayne, Indiana must be considered. Through research, it was discovered that Fort Wayne, Indiana receives about 5.25 hours of peak solar radiation a day. The solar panels would need to completely charge the batteries in one day; therefore, the solar panels will need to deliver approximately 220 watts, capacity of the batteries divided by the hours of peak solar radiation on a day. The solar panels are dependent upon the load that needs to be delivered to the mechanical system and cost more than any other component in the electrical system, therefore; due to cost constraints, the design uses one 85 Watt solar panel.

### Regulator

The regulator is used to charge and protect the battery pack as well as protect the solar panels. If the batteries were connected directly to the solar panels, several problems would arise. First of all, the solar panels would not produce a constant voltage to charge the battery pack. Second, if there was no sunlight, the panels would not produce a voltage. However, since they are still connected to the batteries, current would flow through the panels and damage them. Most of the regulators made for solar application contain safety features that prevent damage to the solar panels and batteries. The selection of the regulator depends on the voltage and current of the system. The regulator must provide the correct voltage to charge the batteries and have a high enough rating for the current in the system. The regulator to be used in the design is the Sun Saver SS-10L-12. This regulator charges a 12 volt battery pack.

### DC-DC Converter

A DC-DC converter must be used to provide power to the control circuit. Power to the control circuit is provided by a DC-DC converter that converts 12 volts to 5 volts and a second converter that converts 5 volts to 3.3 volts. It was decided that there should also be a LCD module to display the current temperature and the desired temperature.

### Control Circuit

The control circuit will be responsible for keeping the system within the specified operating parameters. The circuit will use feedback data from a temperature sensor mounted within the conditioned space and control the mechanical system to maintain a desired temperature. The signal from the temperature sensor will go to the microcontroller. Based on this signal, the microcontroller will decide whether to turn the cooling system on or off by sending a control signal. This control signal will be sent to the relays which control the power to the mechanical system. One signal will be sent to the relay controlling the fan and another signal will be sent to the relays controlling the two pumps and solenoid valve. These signals will be buffered by two optocouplers. The desired temperature may be input by the user through a user control interface

consisting of two momentary push buttons to increment the desired temperature  $\pm 1^{\circ}\text{C}$ , a switch to control the fan, and a switch to turn the system off. This data may be viewed by the user through a 2 line by 12 character LCD module. This LCD module will display the current temperature of the conditioned space, which is determined by the temperature sensor, and the desired temperature as input by the user. The circuit needs both 3.3V and 5V, so a DC-DC converter that increases 3.3V to 5V will be incorporated into the control circuit.

- *Microcontroller*

The microcontroller to be used in the design of the control circuit is the Silicon Labs C8051F920. This microcontroller uses a 3.3V supply voltage and features 24 I/O pins. The design will require the use of 22 of these I/O pins, 2 of which will be used for the external crystal. All of the specifications for the microcontroller were found in the C8051F9xx data sheet. The HC-49UX quartz crystal will be used to set the clock of the microcontroller to 2 MHz. The crystal circuit can be seen in both **Error! Reference source not found.** and **Error! Reference source not found.**

- *Temperature Sensor*

The temperature sensor to be used in the design is the DS1621 Digital Thermometer. A digital sensor is more practical for this application than an analog sensor because it can be easily interfaced with the microcontroller and the signal from the sensor will not need amplification. The sensor has a wide power supply range (2.7V to 5.5V) so the 3.3V from the DC-DC converter will be used as the supply voltage. The temperature is measured from  $-55^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$  in  $0.5^{\circ}\text{C}$  increments. The data is read as a 9-bit value through a 2-wire serial interface. The sensor features programmable hysteresis which allows the user to define a temperature range and sends a signal,  $T_{\text{out}}$ , when the temperature of the conditioned space is outside that range. The sensor is in an 8-pin DIP package and will be connected to 6 of the microcontrollers I/O ports. All of the specifications for the digital thermometer were found in the DS1621 data sheet.

- *Relays*

The relays used in this design are Fujitsu's JS-5E-K electromechanical relays. The relays used in this design must have at least a 4A rating on the contact, the coil needs to be triggered by 5V and the cost must be minimal. The JS-5E-K was selected based on these criteria and features an 8A current rating and a must operate voltage of 3.5V.

- *Optocouplers*

The optocouplers used in the design will be Avago Technologies' ACPL-772L 3.3V/5V High Speed CMOS Optocouplers. This optocoupler was selected primarily for its dual voltage operation. The input to the optocoupler will be supplied with 3.3V from the microcontroller while the output will be supplied with 5V. This eliminates the problem of the 3.3V signal not being high enough to be recognized by the relays. The ACPL-772L also has a wide temperature operation range which is necessary for our application.



- *LCD Display*

The LCD display to be used in this design is Densitron Technologies' LC4212 2 line by 12 character LCD module. This display requires a 5V supply voltage and is the main reason the 3.3V to 5V DC-DC converter must be incorporated into the design. The purpose of the display is to provide the user with data and to add to the ease of operation of the system. The top line of the display will show the current temperature of the conditioned space read from the digital thermometer. The bottom line will show the desired temperature of the conditioned space as input by the user.

- *User Interface*

The user interface will consist of 2 momentary push buttons and two switches. They will be labeled and mounted onto the control circuit in proximity to the LCD module. The 2 momentary push buttons will be used to increment and decrement the desired temperature by  $\pm 1^{\circ}\text{C}$ . Actuating these buttons will also adjust the reference temperature range in the program and the microcontroller will control the mechanical system accordingly. One switch will be used to control the fan and the switch turns the system off. The switch that turns the fan on will allow the fan to run while the cooling cycle is off. However, while the cooling cycle is on, the fan must always be on. This problem will be addressed in the programming.

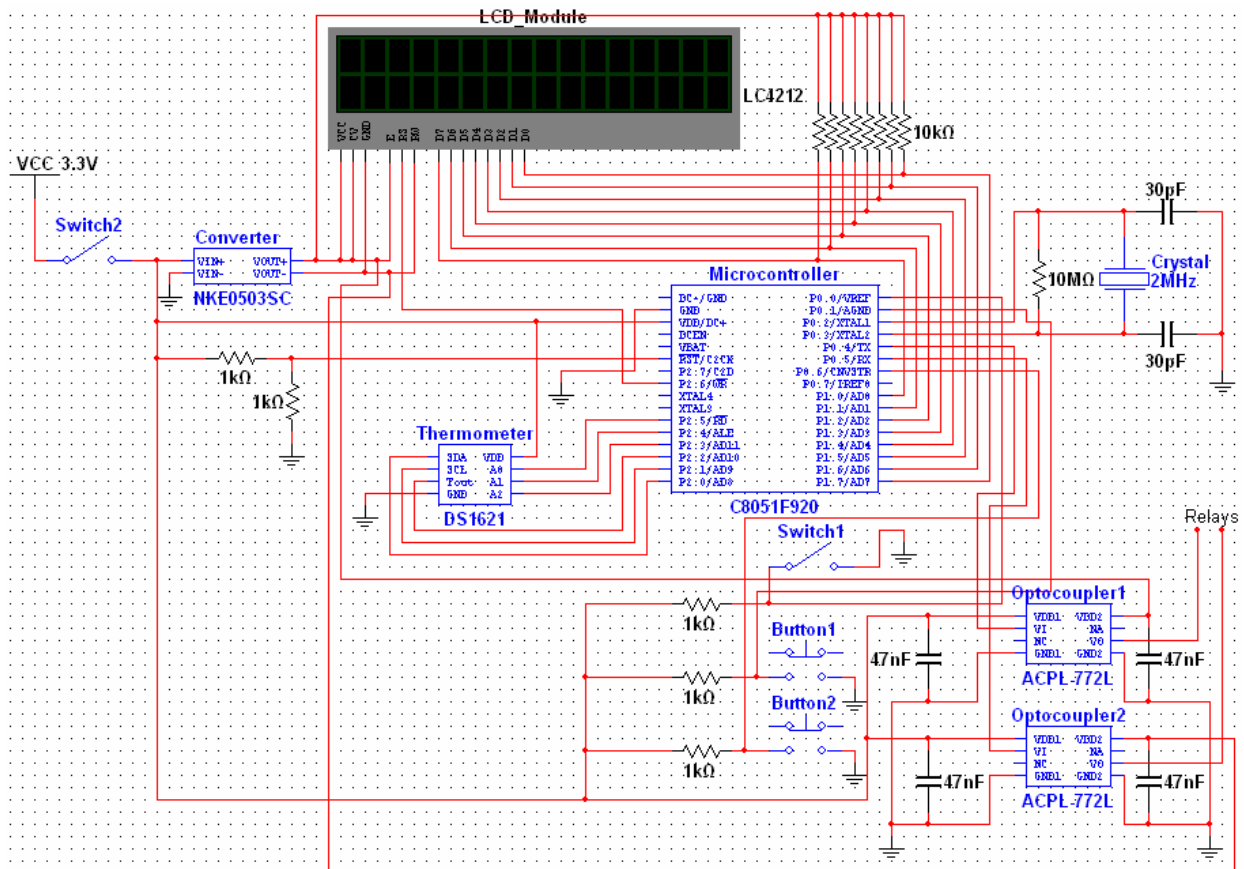


Figure 14: Schematic of Low Voltage Control Circuit

## Program

The program to be run on the microcontroller will be written at a later date but a flow chart of how this program will run is seen in Figure 15. The program will start and initialize input and output ports as well as some variables. The program will then call three functions, one that will read the temperature, one that will display the current temperature and desired temperature on the LCD display, and one that will read if a button has been pressed. The program will then continue. If the fan switch is on, the cooling system will be shut down and the fan will turn on. This will continue until the switch is turned off. The program then goes through two conditional *if* statements that will determine if the mechanical system should be turned off or on. If  $T_{out}$  is high, which means that the temperature is above the range, the system will activate. If  $T_{out}$  is low, which means that the temperature is below the range, the system will shut down. The process of the *if* statements will then repeat in a continuous loop.

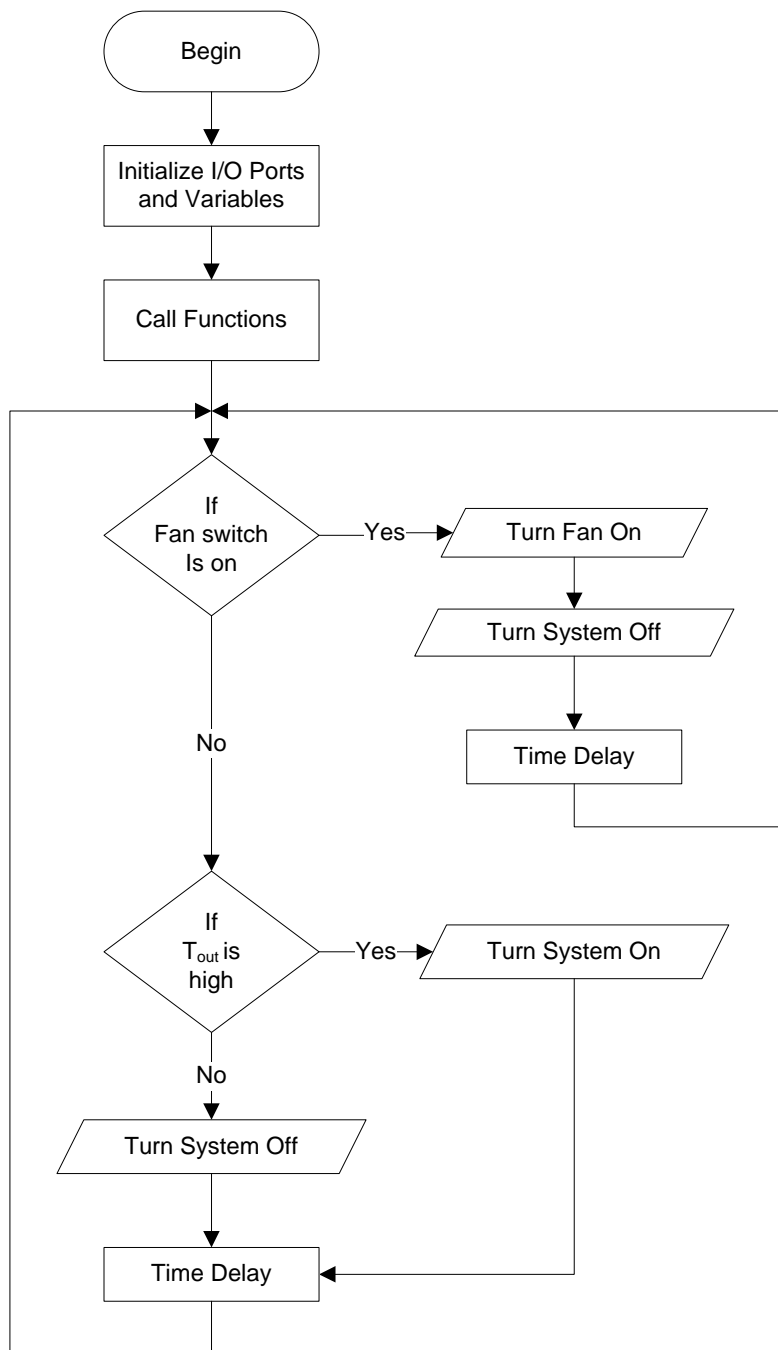


Figure 15: Flow Chart

## **Section II: Building Process**

## Mechanical Design

To begin the building process, a cart had to be built that would fit all of the components of the system. The cart was built out of metal tubing and sheet metal that was donated by Precision Laser. The size of the cart is 27"x34"x36". Building on the cart began by cutting the legs and crossbars of the cart to the appropriate length. This framework was then welded together. To install the bottom shelf, 5/16" holes were drilled and tapped to bolt down the shelf.

While waiting for parts to arrive, a water tank was constructed from sheet metal to be used in the heat source loop. An immersion heater was installed into the side of the water tank to help heat the water since enough solar collectors couldn't be purchased due to budget constraints. Two holes were cut into the side of the water tank and threaded fittings were welded over the holes so that piping could be installed later. Feet were also welded to the bottom of the tank so that it could be mounted to the bottom shelf. Due to the weight of the tank once filled, extra crossbars were welded to the frame below the bottom shelf for extra support. Picture of the water tank and cart can be seen in Figure 16 and Figure 17.

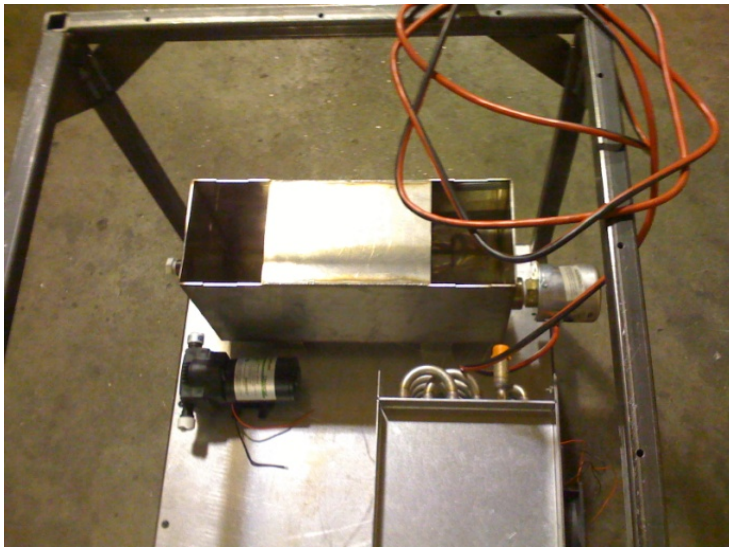


Figure 16: Picture of Cart with Water Tank

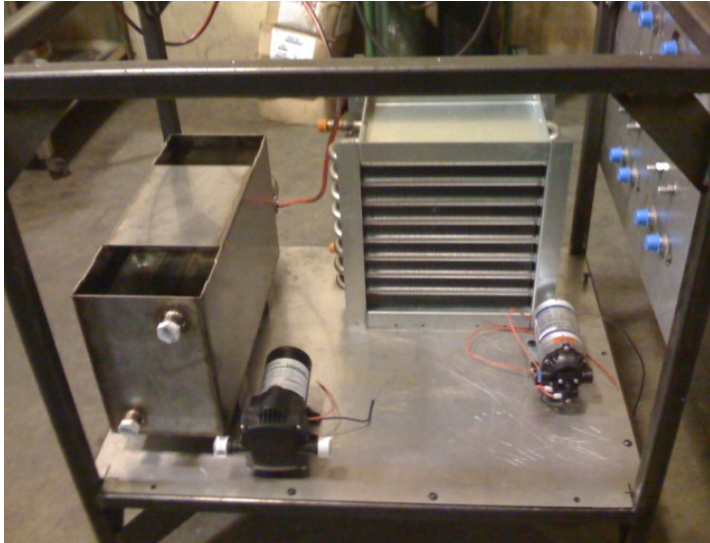


Figure 17: Picture Showing Inlet and Outlet of Water Tank

The first piece of equipment that was received was the generator. Because it was previously used as an air purger, some work needed to be done to it to convert it into the generator that was needed. The first step in the transformation was to remove the top and bottom caps and then to begin scrapping off the gaskets. The bolts in the top of the purger were able to be removed but the bolts in the bottom had rusted into the purger. These bolts were simply cut at the base and the bottom cap was discarded.

Coiled tubing was already installed in the purger but didn't sit low enough in the body of the generator. Extensions were welded onto the coils and then pressure tested. A baffle was then constructed to sit down in the generator to aid in the heat transfer. The original top cap was salvageable and used in the final generator design but as previously mentioned the bottom cap was discarded. Because the bolts in the bottom of the generator had to be cut, the holes were not usable. New holes were drilled and tapped to apply a new cap. A new cap was then constructed from  $\frac{3}{4}$ " steel. The cap and the holes in the cap for the bolts were cut out using a laser cutter. The cap was then milled to fit over the lip on the bottom of the generator. A picture of the generator can be viewed in Figure 18.



Figure 18: Picture Showing Generator

The next components that were received were the fans and the evaporator. Because the air has to be pulled across the evaporator, the fans needed to be mounted to one side of the evaporator. A plate was designed and then cut using the laser cutter to fasten the three fans to and then attach to the evaporator. Once the plate was attached to the evaporator, the evaporator could be mounted to the bottom shelf as well. Angle iron was used to attach the evaporator to the bottom shelf. An overhead view of the evaporator and a picture of the fan plate mounted to the evaporator can be seen in Figure 19 and Figure 20 respectively.

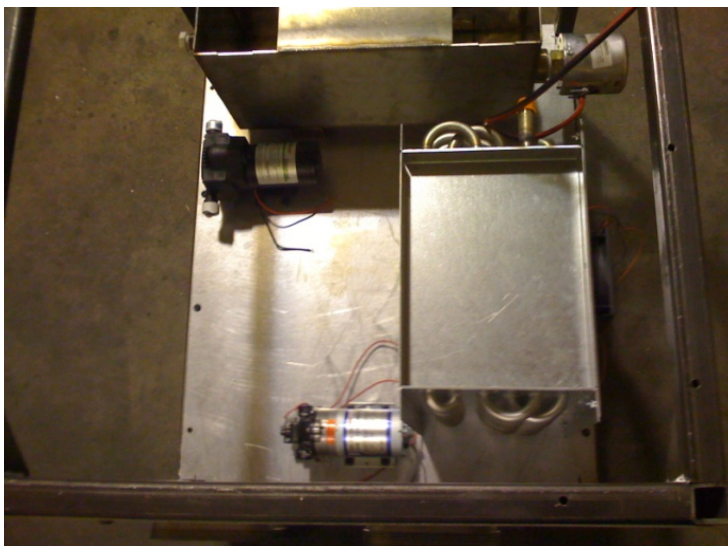


Figure 19: Overhead View of Evaporator



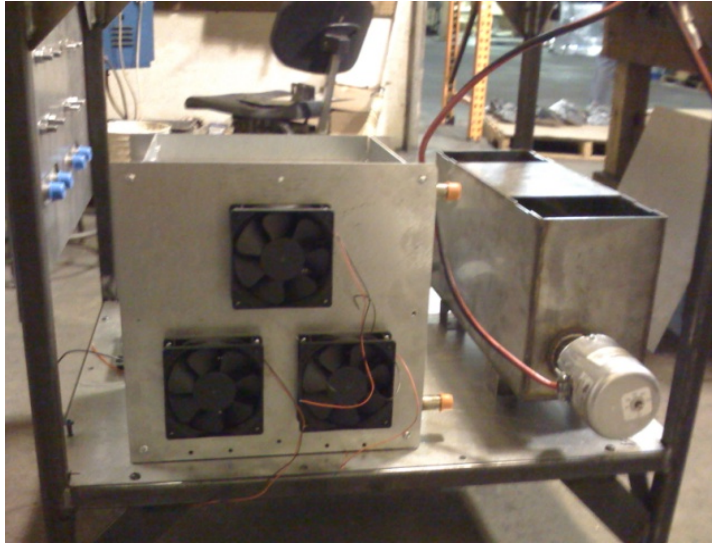


Figure 20: Picture of the Fan Plate

The heat exchangers were the next components that needed to be mounted to the cart. The heat exchangers were initially to be installed horizontally with one above the other. After reading the literature that came with the heat exchangers, it was discovered that the heat exchangers couldn't be install as planned. They had to be installed vertically, and it was decided that the best place to install them was at one end of the cart alongside each other. In order to accomplish this, a panel needed to be made to mount the heat exchangers to and then attach the panel to the cart. As with the panel for the evaporator, the panel for the heat exchangers was cut using the laser cutter. Holes were drilled and tapped into the cart frame so the panel could get bolted down to the frame. The heat exchanger panel is shown in Figure 21.



Figure 21: Flat Plate Heat Exchanger Panel

The generator was the next component to be mounted to the cart. Because the strong absorbent solution needs to flow into the generator/absorber heat exchanger, the generator needed to be



mounted above the heat exchangers. A frame was constructed to attach to the top of the cart's framework. Two crossbars were also installed in the top of the cart to attach the generator mount to for increased stability. Two holes were then drilled into the generator mount to bolt the generator to the mount. The holes used on the generator for this mounting purpose were holes that were already drilled and tapped into the generator. Figure 22 shows the generator mounted.

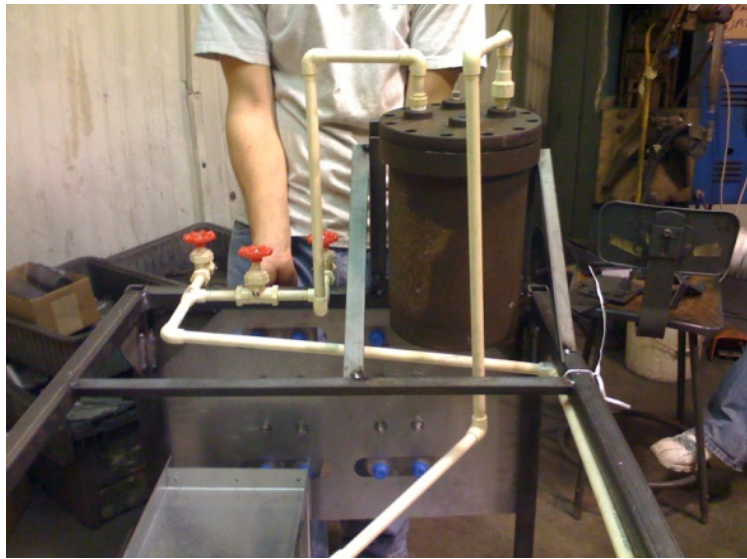


Figure 22: Picture Showing Generator Mounted

Once the generator was mounted on the top of the cart, a shelf was constructed to cover the other half of the top of the cart. Because the generator also exits to the condenser and then the condenser to the thermostatic expansion valve and the evaporator, it was decided that the condenser would also do best on the top shelf. The condenser is similar to the absorber and generator/absorber heat exchangers in that it had to be mounted in the vertical position. To keep the condenser on the top shelf, a bracket was made and attached to the shelf for the condenser. Figure 23 and Figure 24 show the top shelf and condenser within the system.



Figure 23: Picture of Mechanical Design with Top Shelf and Condenser

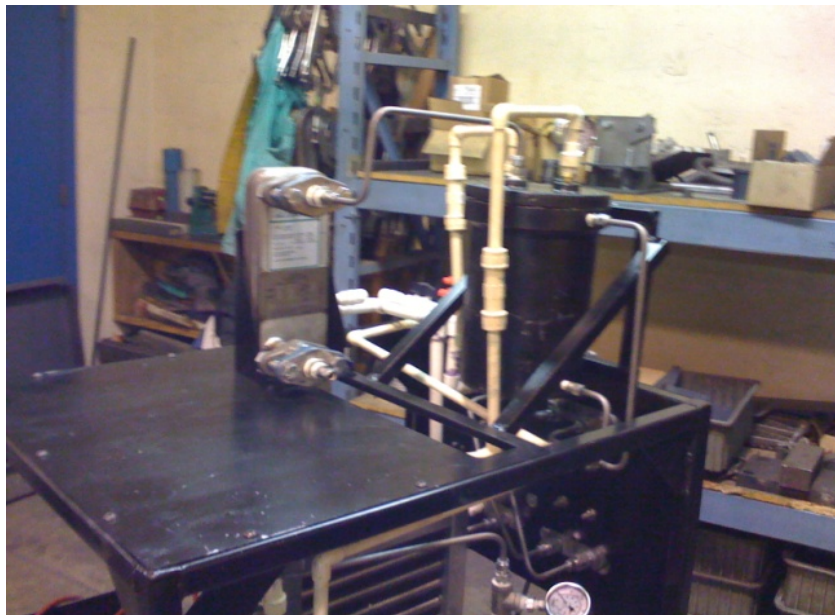


Figure 24: Close up of Top Shelf and Condenser

The absorber was made and donated to us by Shambaugh & Sons, a picture of it can be seen in Figure 25. Once the absorber was received, legs were welded to the bottom of the absorber so that it could be more easily attached to the bottom shelf of the cart. Once the absorber was

attached, the pumps were installed on the bottom of the cart. CPVC pipes were next cut and fit into the system for the heat source loop. Pipes had to be run from the tank to the pump, from the pump to the generator, from the generator to the valves for the solar collector to be connected to, and then back to the tank. To make the emptying of the tank easier, a threaded fitting was welded to the side of the tank so that a plug could be inserted and removed. Three valves were used where the solar collector could be connected to the system. They were arranged in such a way that the water could run to the solar collectors and the thru valve was closed or the valves to and from the solar collector could be closed and the water could flow through the thru valve back to the water tank. The heat source loop is shown in Figure 26, Figure 27, and Figure 28.



Figure 25: Absorber made by Shambaugh & Sons

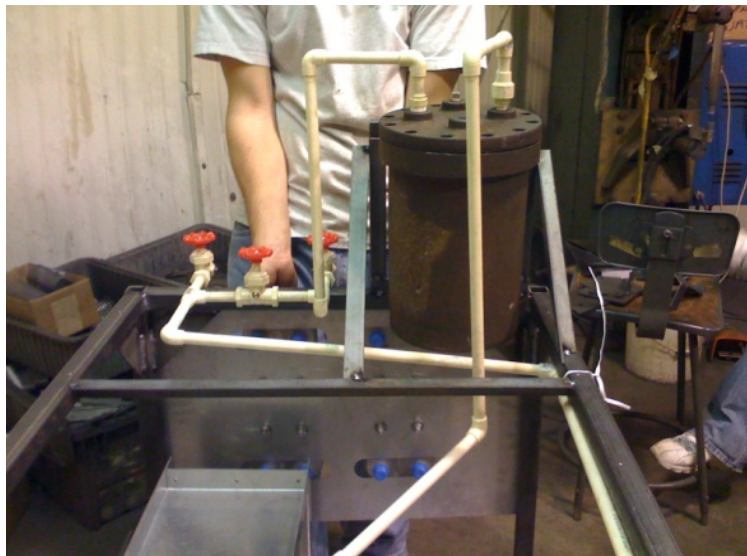


Figure 26: Top Portion of Heat Source Loop

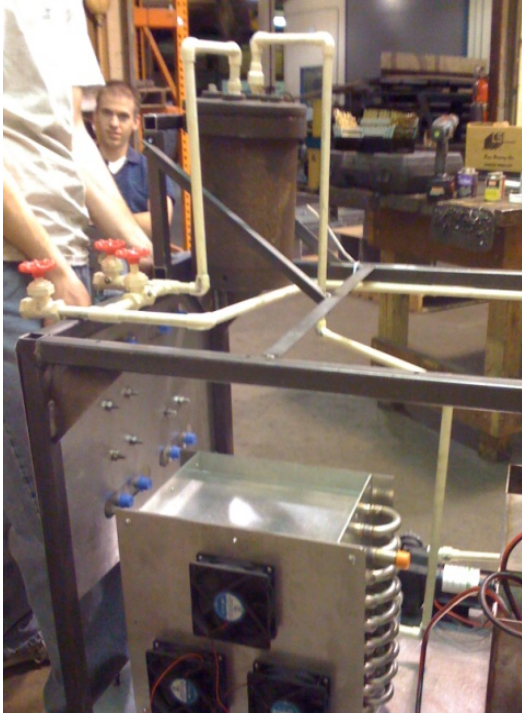


Figure 27: Heat Source Loop with Solar Collector Valves





Figure 28: Heat Source Loop with Pump and Water Tank

Once all of the components and the pipes for the heat source were figured out, they were removed from the cart so that it could be painted along with the generator and the absorber. Figure 29 is a picture of the system with the cart painted. While everything was off the cart, plates were welded to the bottom of the cart legs so that the casters could also be installed. Once the paint had dried and the casters were installed, all of the components and the heat source piping were reinstalled.



Figure 29: System with Painted Cart

The cold water loop was installed to the condenser and the absorber heat exchanger. PVC pipe was used for the piping. Because tap water is to be used for the cold water loops, it was decided that one inlet was needed and then could be branched off to each component. The cold water loop is shown in Figure 30. On the exit of the cold water loops, valves were installed to help control the flow rate through the components. Hoses were installed past the valves to run the tap water to a drain.



Figure 30: Cold Water Loop

Steel Yor-Lock fittings were installed to all of the threaded fittings in the system that the refrigerant would be running through except the condenser. Flanged ammonia fittings were used on the condenser due to its construction. Pressure gauges were installed on the absorber and the generator to measure both the high and low pressures of the system. Flow meters were then installed on the heat exchanger panel on each side of the absorber heat exchanger as seen in Figure 31. This was done so that the flow rate of both the weak absorbent and strong absorbent solutions could be measured. This location was picked for ease of connection between the components. Using a 3/8" tubing bender, pipes were bent to fit within the system and connect the components in the system. Piping between the top and bottom shelves is shown in Figure 32. The only piping not installed was those connecting to the thermostatic and hand expansion valves.



Figure 31: Flow Meters



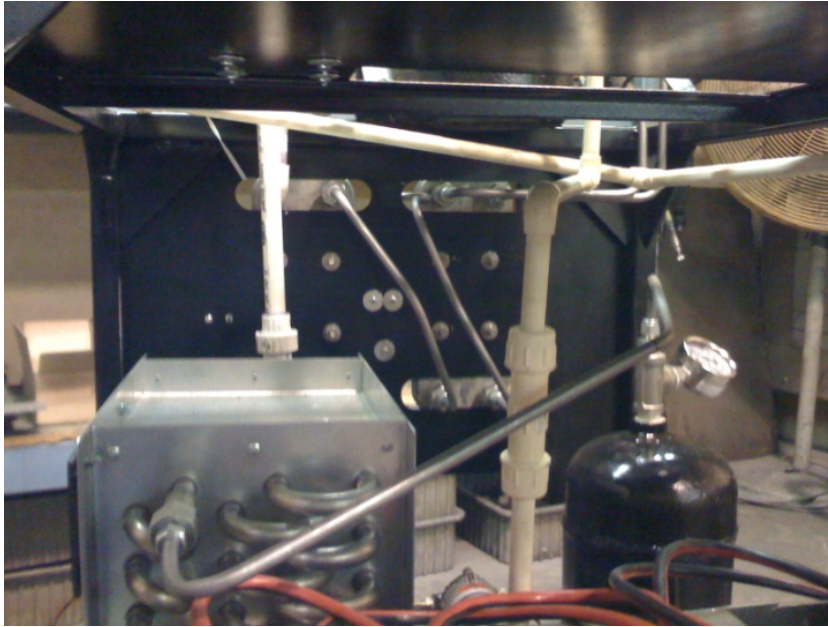


Figure 32: Connection Piping

The system was then transported to Shambaugh & Sons. Mike Christianer at Shambaugh & Sons installed the thermostatic expansion valve and the hand expansion valve. The tubing that connects to the expansion valves were then bent and installed. Figure 33 contains a close up of the thermostatic expansion valve. Also at Shambaugh & Sons, gaskets were installed in the top and bottom caps of the generator and in the condenser fittings. The system was then transported back to Precision Laser to be leak tested.



Figure 33: Ammonia Thermostatic Expansion Valve

The system was pressurized to 110 psi to check for leaks. Many leaks were found around the fittings and the caps of the generator. The pressure in the system was released to begin fixing the



leaks. The fittings were tightened down and the caps were removed from the generator. The gaskets for the generator were re-cut and greased to eliminate leaks. The gaskets in the condenser were also greased to help eliminate leaks. The system was then pressurized again and only a few leaks were found in the fittings. The fittings were then tightened down more and on the third leak test no leaks were found.

Once the system was leak proof, the duct work to the space, shown in Figure 34, and the thermocouples, shown in Figure 35, were integrated into the system. For the ductwork, a dryer duct was used. Two plates were made to attach each side of the evaporator to the ductwork. One side of the evaporator is used to pull air from the space through the evaporator and the other side pushes the air back into the evaporator. On the side of the evaporator with the fan plate, an offset was made to attach the ductwork plate to the fan plate.

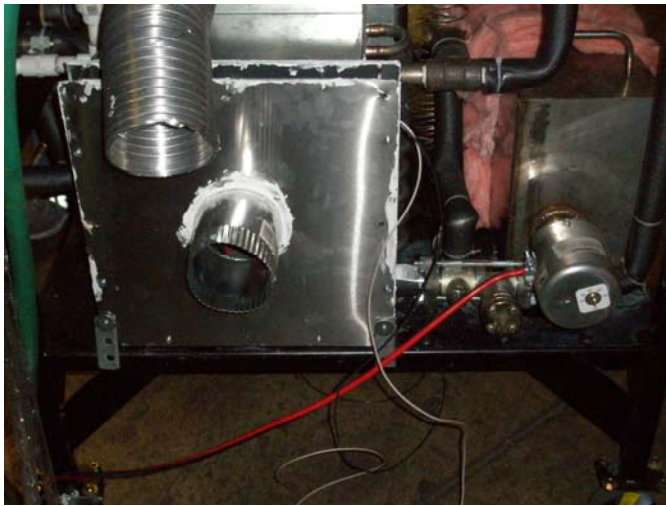


Figure 34: Ductwork in System



Figure 35: Thermocouples and Digital Readout

Twenty thermocouples were made to be used in the system and to have backups. Seven of them were installed on tubing through the system, three were installed in the inlet and outlets of the cold water loops, and three were installed in the heat source. Metal sleeves were cut to fit over

the tubing in the system in order to house the thermocouples. JB weld was applied to each end of the sleeves to attach them securely to the tubing. On the inlet of the cold water loops, a hole was drilled into the fitting and JB welded to keep the thermocouple in place. In the outlet of the water loops, the thermocouples were put directly into the stream in the exit hoses. For the heat source, thermocouples were installed in the fittings on the inlet and outlet of the water tank as well as the valve from the outlet of the solar collector. The heat source thermocouples were installed by drilling a hole in the fitting and putting JB weld in the hole to hold the thermocouple in place.

To reduce the amount of heat lost from the system, insulation was added. The connecting pipes and fittings in the ammonia/water loop were insulated with  $\frac{1}{2}$ " pre-slit insulation. The  $\frac{1}{2}$ " pre-slit insulation was also used to insulate the pipes in the heat source loop and at the inlet of the cold water loop due to the thermocouple installed. The generator, generator/absorber heat exchanger, and water tank were insulated with fiberglass sheet insulation. Pictures of the mechanical system with insulation are shown in Figure 36, Figure 37, Figure 38, Figure 39, Figure 40, and Figure 41.



Figure 36: Mechanical System



Figure 37: Generator with Insulation



Figure 38: Generator/Absorber Heat Exchanger with Insulation



Figure 39: Mechanical System

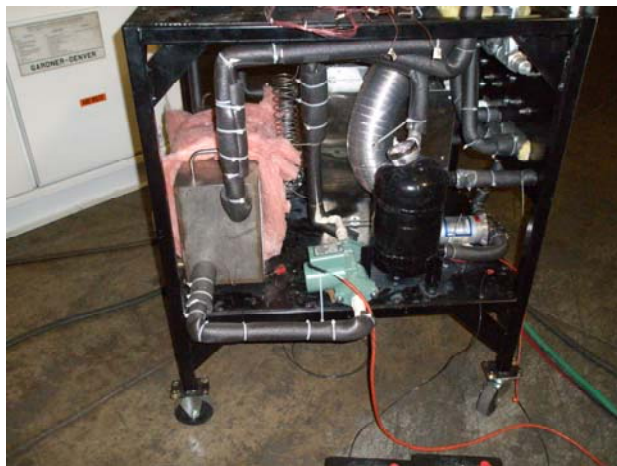


Figure 40: Inside of Cart

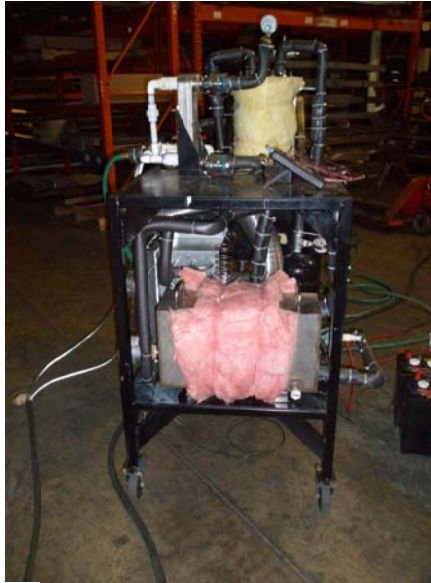


Figure 41: Insulated Water Tank

The system was then transported back to Shambaugh & Sons to be charged with ammonia. The system was charged by pouring water into the generator. Liquid ammonia was then added to the generator as well. To pressurize the system and achieve the concentration, vaporized ammonia is added to the system through a valve in the generator.

The solar collector needed to be mounted in such a way that it was at a 45 degree angle and could face southwest for optimal use. Due to the location restrictions, the solar collector needed to be mounted to a cart. A 2x4 frame was constructed to achieve the 45 degree angle and was then mounted to a cart provided by IPFW. The solar collector needed fittings attached to the inlet and outlet piping so that it could be incorporated into the system. Threaded garden hose fittings were soldered to solar collector pipes. Threaded garden hose fittings were also installed in the solar collector valves in the heat source loop so that the solar collector could be added and removed from the system easily. The photovoltaic cell also needed to be mounted with the solar collector on the cart. A 2x4 frame was added to the back of the solar collector frame to house the photovoltaic cell. Mounts for the solar collector and solar panel can be viewed in Figure 42 and Figure 43.





Figure 42: Solar Collector and Solar Panel Mount



Figure 43: Solar Panel Mount

The enclosed space was the last piece of the project to be constructed. Plywood  $\frac{1}{4}$ " thick was used for the walls of the space. They were cut down to construct a 1 meter cube. Due to the thickness of the plywood, 2x4 pieces were attached to the corners of the plywood and used to screw the walls together. To be able to add a heat source into the space, a window was cut into the front of the space. A Plexiglas sheet was used as the window and a hinge and handle were used to allow the window to open and close easily. The window in the space is shown in Figure 44. Two holes were then cut into one of the sides of the space to hook in the return and exit of the ductwork. Caulk was used to seal up both the ductwork connections and the gaps along the edges of the space. Once the enclosed space was completed, the system, space, and solar

collector could all be connected. The system hooked up to the solar collector and the space is shown in Figure 45.



Figure 44: Enclosed Space with Window



Figure 45: System with Space and Solar Collector

## Electrical Design

### PCB

The Ultiboard software was used to design the PCB. Certain considerations had to be kept in mind while designing the PCB. The width of the traces needed to be adjusted based upon the current the trace would be carrying. The traces that carry the highest current include the power to the mechanical system that travels through the relays. Connectors were also added on the outside of the board to connect all the external components, such as the mechanical system, temperature sensor, and the LCD. The design for the PCB can be seen in Figure 46.

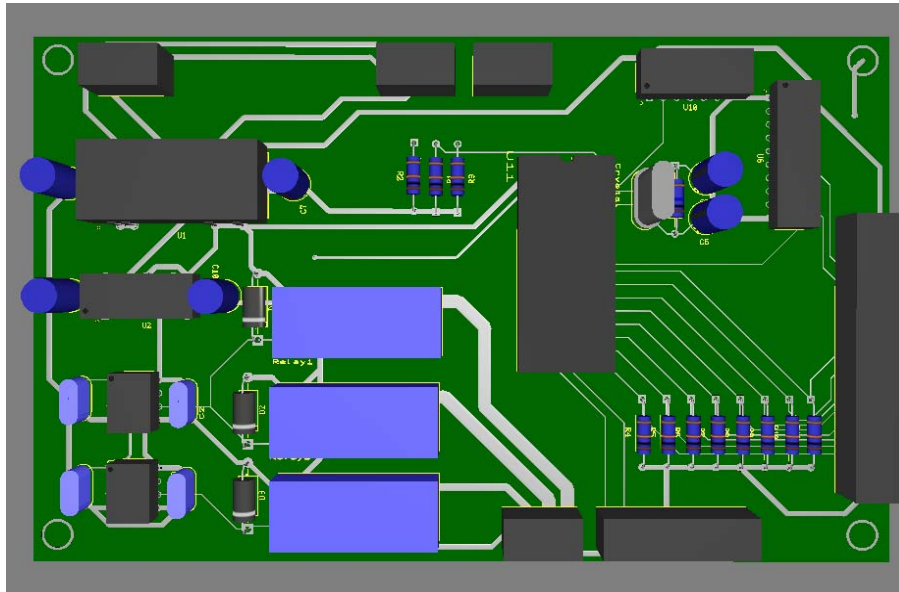


Figure 46: PCB Design

### Modifications

While the basic conceptual design was maintained through the building process, some modifications were incorporated into the previously described detailed design. The first modification was the implementation of a transistor circuit to amplify the current output of the microcontroller. It was found that the current from the optocouplers was not enough to switch the relays. The current that can be supplied from the optocouplers is about 10 mA while the relays require a minimum of 40 mA to actuate. In order to amplify the current, a transistor circuit would be needed. It was decided to amplify the signal directly from the microcontroller rather than amplifying the current from the optocouplers. In the initial design, the optocouplers were used to buffer the output of the microcontroller and to amplify the signal. The optocouplers were used instead of a transistor circuit because there is no leakage current in an optocoupler. However, the leakage current from the transistor circuit is very small and, since a transistor circuit will be needed to boost the signal anyway, it was decided to remove the optocouplers completely so as to decrease the amount of parts and complexity of the design. The port I/O output high current of the microcontroller is listed on the datasheet to be 3mA. This current was actually measured to be approximately 2.3 mA. After implementing the transistor circuit with the signal from the MCU as the input, the output from the amplifier was measured to be 68.45



mA which is more than enough current to actuate the relays. The transistor circuit in can be seen below in Figure 47.

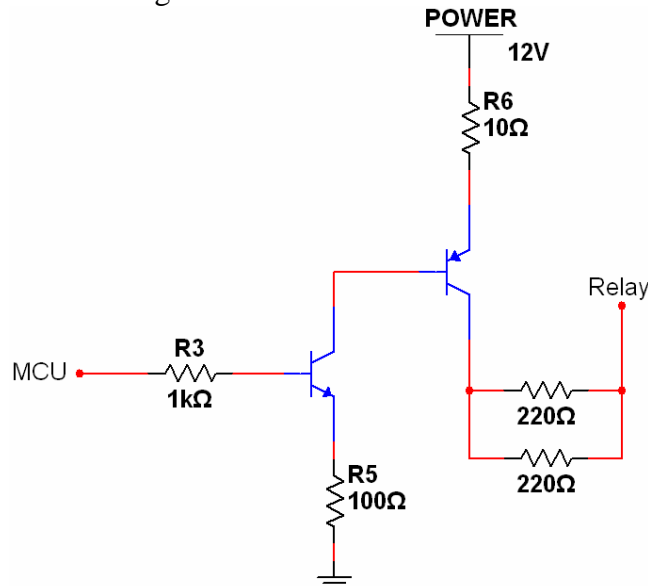


Figure 47: Transistor Amplifier Circuit

Another modification that was incorporated into the design was the implementation of the C8051F930 development board instead of the single chip. This decision was made primarily due to time constraints and because of the ease of implementation. The development board also provides all the same functionality without having to program an external microchip. Incorporating an external microchip into the design would require the flash memory to be programmed as well as a significant amount of additional programming including initializing and using the external crystal oscillator. The development board also allows in-system programming and debugging while the external microchip would require additional circuitry to allow this function. To power the development board, 2 AAA batteries were used; however, the board could also be powered by the 3.3V off of the PCB. This decision was made to cut down on the amount of wires inside the box and also to allow programming of the development board without being connected to the two 6V batteries.

The last modification was the implementation of a 2-digit 7-segment LED display. During the building process, difficulty arose while trying to implement the LCD. The LCD requires a higher input than the microcontroller can provide. Because of this, the LCD had to be tested with pull-up resistors. During the testing process, the LCD was not receiving the correct initialization code; therefore, it was decided to implement a 2-digit 7-segment LED display. To implement the display, two decoders were needed to convert the byte of binary data to the correct output to display the two digit decimal number as shown in Figure 48. However, this only allows displaying one temperature at a time. To resolve this problem a switch was used to select which temperature would be displayed. To implement these changes, the components were placed on separate boards, soldered, and then wired together.

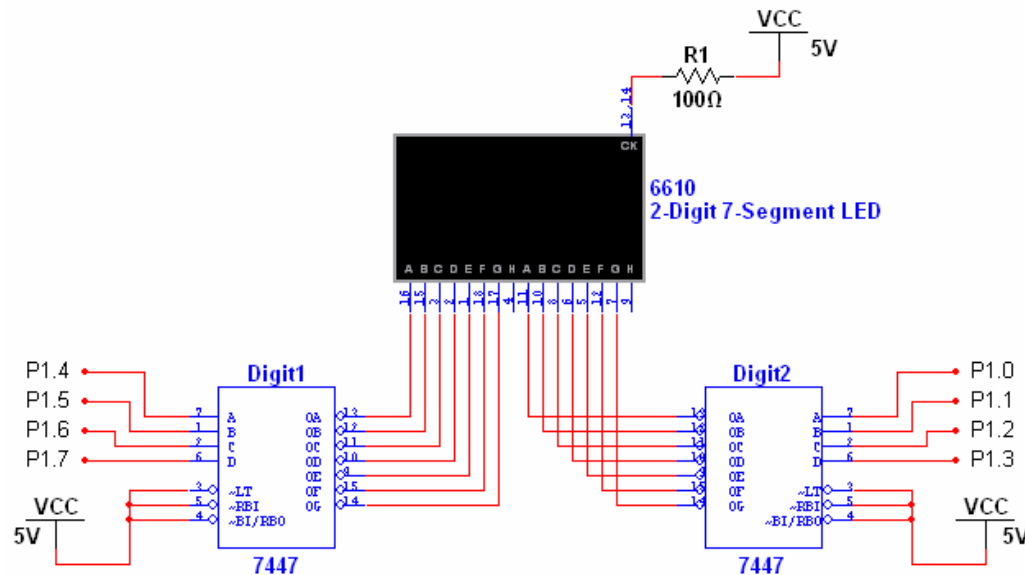


Figure 48: 7447 Decoder to 2-Digit 7-Segment LED display circuit

With the implementation of the development board, the PCB no longer provides the majority of the connections. In order to interface the development board, the expansion I/O connector (P1) was utilized. The 96-pin connector provides access to all signal pins of the C8051F930 device except for the C2 debug interface signals. A small through-hole prototyping area was also provided on the board and was used to power the temperature sensor with the necessary 3.3V. Table 1 shows the pin descriptions for the P1 connector. The P1 connector was used to connect the temperature sensor, encoders, buttons and switches directly to the development board. Figure 49 shows the pins that were used in this design. Port 1 was used to send data to the encoders, D1 is the MSB of the left most digit and D2 is the MSB of the right most digit.

Table 1: P1 Connector Pin Descriptions

Bottom Row Pin #	Description	Middle Row Pin #	Description	Top Row Pin #	Description
1	+3 VD	1	GND	1	nc
10	nc	10	P0.7/IREF0	10	P0.6/CNVSTR
11	P0.5/RX	11	P0.4/TX	11	H
12	H	12	P0.1/AGND	12	P0.0/VREF
13	P1.7/AD7	13	P1.6/AD6	13	P1.5/AD5
14	P1.4/AD4	14	P1.3/AD3	14	P1.2/AD2
15	P1.1/AD1	15	P1.0/AD0	15	A7-Latch
19	nc	19	nc	19	P2.3/A11
20	P2.2/A10	20	P2.1/A9	20	P2.0/A8
21	P2.6/WR	21	P2.5/RD	21	P0.2
23	P2.0	23	P2.4/ALE	23	nc

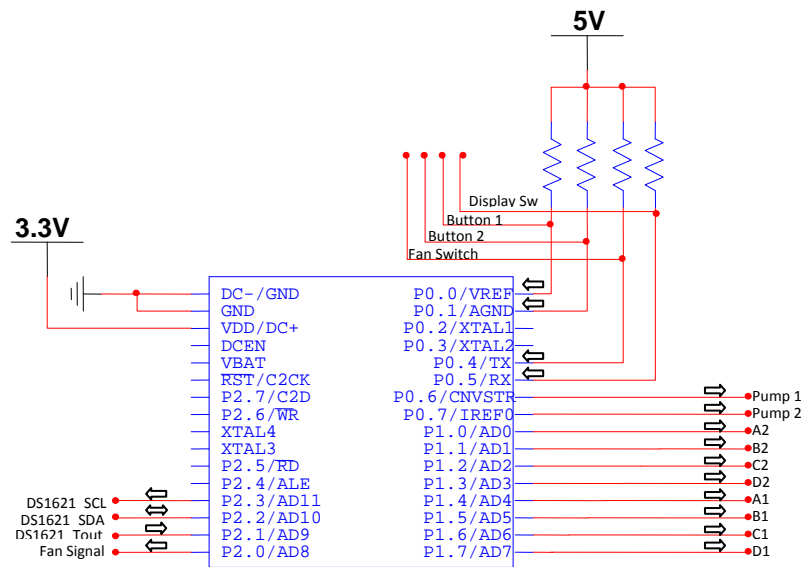


Figure 49: MCU Pin Connections and Descriptions

### **Section III: Testing**

## Parameter Measurements

Parameters are quantities that define characteristics of the system. The parameters are measured to verify the design and operation of the prototype system. These parameters are used to ensure that the system meets the requirements set forth by the problem statement.

## Mechanical Design

A schematic showing all state point designations is shown below in Figure 50.

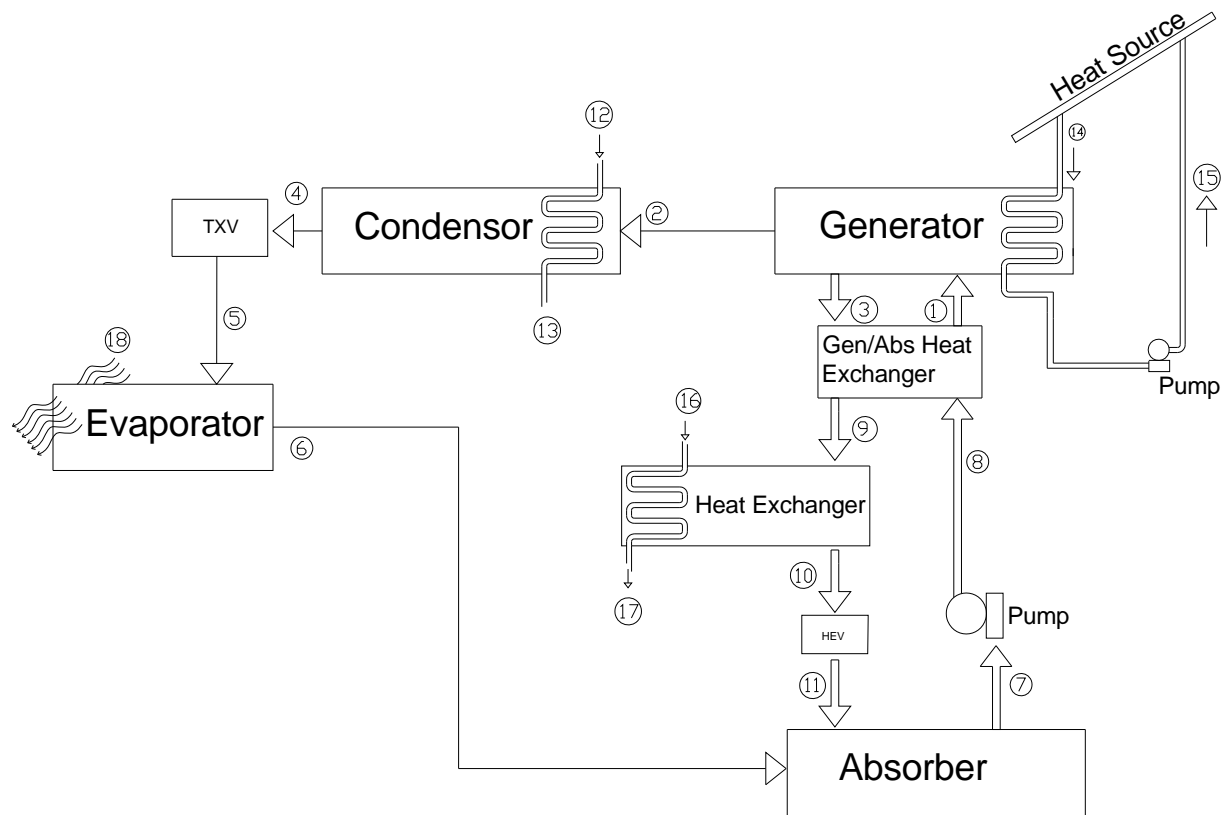


Figure 50: Schematic of mechanical state point designations

## Temperature

Temperature is measured using a thermocouple. A thermocouple generates a current proportional to its' temperature. The thermocouples are going to be surface mounted to the connecting pipes. They will be attached underneath the insulation that will be wrapped around the pipes to help lessen heat loss. The points at which temperature will be measured are shown in figure 1.

18. Conditioned space: This is done to verify that the problem statement is met. The object of the system is to use an absorption cycle and solar energy to cool a space. The space is to

be cooled to a desired temperature, 74°F. This is to be accomplished by supplying a specific cooling load to the space as is specified in the design, 1.5 kW.

5. Inlet of the evaporator: The temperature at this location in the system must be measured in order to verify the cooling load of the evaporator.
6. Outlet of the evaporator: This temperature was specified specifically by the choice of thermal expansion valve. This value is set by the thermal expansion valve properties. This temperature is designed to be 46°F. This is necessary to prevent the condensation on the evaporator from freezing and causing it to function improperly.
14. Inlet to heat source: The temperature at the inlet of the heat source will be measured in order to calculate the heat transfer of the heat source (2.6kW).
15. Outlet of the heat source: The temperature at the outlet of the heat source will be measured in order to calculate the heat transfer of the heat source (2.6kW). This temperature must also be adequate to evaporate ammonia from the weak absorbent solution entering the generator.
3. Outlet of generator to generator/absorber heat exchanger: This temperature will be measured to verify the effectiveness of the generator based on our EES model.
1. Inlet of generator from generator/absorber heat exchanger: This temperature will be measured to verify the effectiveness of the generator based on our EES model.
2. Outlet of generator to condenser: This temperature will be measured to determine the state of the refrigerant (ammonia) as it exits the generator.

Cooling water loops: Temperature will be measured at the following state points in order to calculate the heat transfer rate in their respective components.

- Condenser water inlet: 12
- Condenser water outlet: 13
- Absorber heat exchanger water inlet: 16
- Absorber heat exchanger water outlet: 17

### Flow Rate

Flow rates are measured with flow meters. Volumetric flow meters will be used. Flow meters will be mounted in series with the connecting pipes in various locations. These locations can be seen in figure 1 and are explained below.

Cooling water loops: Flow rates will be measured at the following state points in order to calculate the heat transfer rate in their respective components.

- Condenser water inlet: 12
- Absorber heat exchanger water inlet: 16

14. Outlet of heat source: This flow rate will be measured in order to calculate the heat transfer from the heat source. If the design works properly the mass flow rate from the heat source should be set to 0.5 kg/s.
7. Outlet of absorber: The mass flow rate of the weak absorbent solution at this point should be 0.08 kg/s. This value in conjunction with the flow rate of the strong solution will be used to calculate the mass flow rate of refrigerant (ammonia) leaving the generator at state point 2.
3. Outlet of generator to generator/absorber heat exchanger: The mass flow rate of the weak absorbent solution at this point should be 0.078 kg/s. This value in conjunction with the flow rate of the strong solution will be used to calculate the mass flow rate of refrigerant (ammonia) leaving the generator at state point 2.

### Pressure

Pressure is going to be measured with dial pressure gauges. The pressure drop across the system will be set with the hand expansion valve at an ideal drop of 2 bar. The pressure within the absorber will be measured with an ammonia pressure gauge. The pressure in the absorber should be 5.8 bar. The pressure within the generator will be measured with an ammonia pressure gauge. The pressure in the generator should be 7.8 bar.

### **Electrical Design**

#### DC DC Converters

Apply DC input with a power source and measure output voltage and current. Adjust input by  $\pm 20\%$  for the 12 to 5 V converter and  $\pm 10\%$  for the 5 to 3.3 V converter and measure the changes in output. These measurements will verify that the convertors will provide a sufficient voltage for the control circuit.

#### Voltage Regulator

Apply DC input with a power source and measure output voltage. In order to measure the voltage regulator's performance with a varying input, the voltage will be varied by the range of the possible voltage output of the solar panel, 0 to 17V. The output will be connected to a load and the voltage across this load will be measured. This voltage measurement will provide the range of voltage from the solar panel that will be useful in charging the batteries.

#### Batteries and Voltage Regulator

The purpose of this test is to determine how much time it will take to drain the batteries and to test the low-voltage disconnect for the voltage regulator. For this test, the batteries will initially be fully charged. The battery will be connected to the same load as the mechanical components

will provide, 300W, and will be left running until the low-voltage disconnect from the regulator disconnects the load from the batteries. The time between the start of the test to the low-voltage disconnect will be measured and the voltage across the batteries will also be measured.

#### Power System (Solar Panel, Batteries, Voltage Regulator)

The solar panel will be connected to the regulator which will be connected to the batteries. This test will have to be done outside with portable measurement equipment. The solar panel will charge the batteries through the regulator. The voltage across the output of the solar panel will be measured as well as the voltage across the batteries. The current from the output of the solar panel will also be measured. This test will also provide the time it will take to fully charge the batteries from the solar panel.

#### Control Circuit (MCU, Thermometer, LCD Display)

The control circuit will initially be simulated using the Keil software. The circuit will be built using the Proteus software and the MCU will be programmed on Keil. The system can then be simulated and the performance of the digital thermometer and LCD display can be observed.

The next stage of testing will be done with the PCB board. The PCB board will be connected and integrated into the system. The digital thermometer and LCD display can then be tested by observing the system perform as a whole.

#### Relays and Optocouplers

The circuit shown in Figure 51 will be used to perform this test. This circuit will test both the input and output of the optocouplers as well as the performance of the relays.



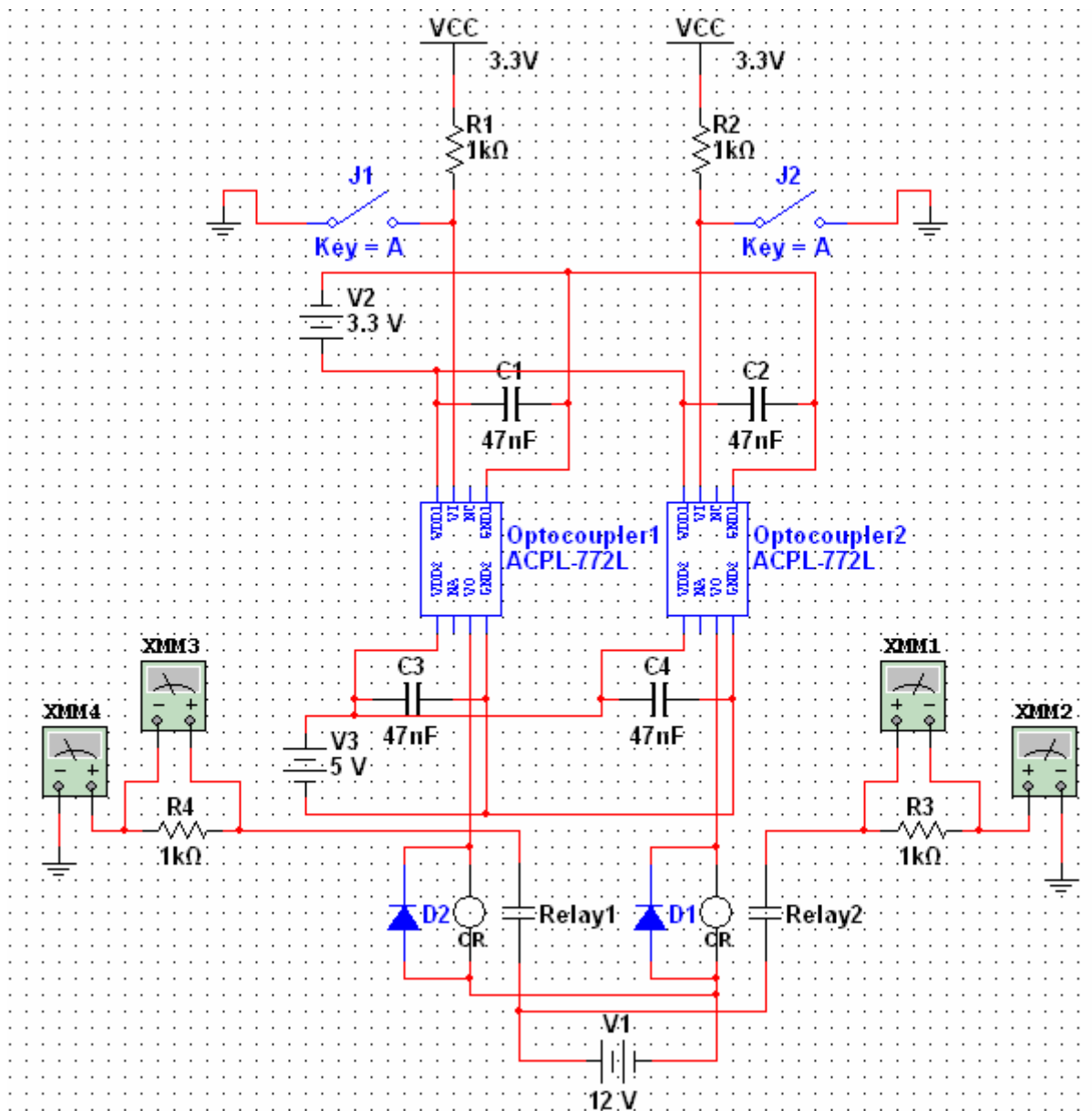


Figure 51: Test circuit for relays and optocouplers

## **Tests During Building**

### **Mechanical Design**

#### Leak Test

As discussed in the building process, the system was leak tested. To leak test, the system was pressurized to 110 psi using compressed air. Soapy water was then squirted around any place in the system where a leak could occur such as the fittings, bolts, and generator gaskets. Once the leaks were found, the pressure was let out of the system. The fittings were tightened down with a wrench. Leaks were also found around the caps of the generator and the condenser. Therefore the caps were removed from the generator. The gaskets were removed and then remade. The gaskets were greased before they were put into the caps and the caps were then refastened to the generator. The gaskets in the condenser flanges were also greased and then the flanges were refastened. The system was then pressurized to 110 psi again to recheck for leaks.

#### Solar Collector Test

The solar collector was placed in the frame that was constructed to house it. Hoses were then attached to the input and output of the solar collector. The inlet hose was then hooked into the outlet of the water tank and the outlet hose of the solar collector was set into the water tank. The water tank was filled with water and extra water was at hand. The extra water needed to be added to the tank once the water starts pumping to make sure the pump doesn't dry out. The water pump was then powered up. A thermocouple was placed in the water tank and then connected to the thermocouple selector and the digital readout. The water was left to circulate over a three hour time from starting around noon. The solar collector was directed in the southwest direction. The solar collector reached 120°F within that time frame.

#### Thermocouple Test

Thermocouples were made to be installed in the system, the cold water loops, and the heat source. Due to the type of thermocouple, the weld has to be submerged completely to work correctly. To install the thermocouples a few ideas were discussed, one was to drill a hole in the fittings and then put the thermocouple in the hole. The next idea was to make a sleeve to hold the thermocouple to the connecting pipes. The first idea was rejected because the integrity of the fitting could be compromised if done incorrectly. Therefore a sleeve was constructed to test the second idea. A thermocouple was secured to the tubing using duct tape and the sleeve was placed over the welded portion of the thermocouple. The sleeve was then secured. To test how well the sleeve would work, cold water was passed through the pipe. A thermocouple was also placed in the water and both thermocouples were installed into the thermocouple selector and the digital readout. The difference in the water flow and the thermocouple was within 0.2°F and is such a small error that it can be considered negligible. The thermocouple was successful and the sleeve idea was used to install the thermocouples.

#### Cold Water Loop Test

Once the PVC for the cold water had set up, a water hose was hooked up to the inlet. There were leaks in the loop where the water entered the condenser. Because quick disconnects were installed in the cold water loop, the section of the loop that had the leak was disconnected and

remade. The coupling connected to the condenser was tightened down before the elbow and quick disconnect were reinstalled.

#### Heat Source Loop Test

The heat source loop was first tested without the solar collector. The water tank was filled  $\frac{3}{4}$  of the way. The pump was then turned on to start circulating the water. This was done to check for leaks in the system. Once there were no leaks found, quick disconnects were added to make it possible to remove the heat source loop when working on other parts of the system.

The next test that was performed was to see how well the immersion heater worked. We turned it to around 200°F. The water heated and the pipes did not leak at the temperature. After a series of testing the water tank and heater, the pump that was used to circulate the hot water failed. The seals in the pump were not designed to withstand the temperature we subjected them to and the seals began to melt. Once the seal started melting, water began to leak from the pump. Pictures of the pump seal can be seen in Figure 52 and Figure 53.



Figure 52: Melted Pump Seal



Figure 53: Hole in Pump Seal

A circulator pump from Taco was then purchased to replace the failed pump. The pump is rated for 230°F. Once the pump was incorporated into the system, the heat source loop was retested.

#### Ammonia/Water Loop Test

At the time the system got charged with ammonia, the pump for the hot water loop had failed and the new circulator pump had not arrived. To test the ammonia/water loop, the ammonia pump was plugged in. The first obstacle that was encountered was that there did not seem to be enough fluid in the loop. Water was added to make sure the pump worked correctly. Once the pump started to work, another problem arose. The flow from the generator, through the heat exchangers, and into the absorber was too slow and the mixture began overflowing into the condenser and evaporator. A valve was added to slow down the flow of the ammonia/water mixture back into the generator. The pump was then started back up to see how the valve worked. The system was pressurized back up to 30 psi.

The valves, hand expansion and the needle valve added to the inlet of the generator, were adjusted to try and get the flow rates stable. The system was then pressurized to 80 psi to check for leaks again because of the valve that had to be put in.

#### **Electrical Design**

The preliminary testing of the project was done throughout the semester. The process involved testing both individual components and programs written on the Keil and the Silicon Labs IDE software. The purpose of the preliminary testing was to ensure the optimal performance of the system by making sure that the individual components were functioning efficiently within the application parameters. The preliminary testing also included the programming of the MCU and breadboard testing of these programs with the required components.

The first stage of preliminary testing involved the programming and simulation of the entire control system on the Keil and Proteus software. The system was programmed for a generic AT89C51 MCU and an LCD module was used instead of the 2-digit 7-segment LED that was

used in the final design. Within the program, the MCU communicated with the DS1621 digital thermometer via the I<sup>2</sup>C serial interface. The MCU would continuously pole the DS1621 for temperature readings and display them on the upper line of the LCD module. Two momentary push buttons were connected to the MCU. The MCU would debounce and read the state of the push buttons. The MCU would increment or decrement a variable depending on which button was pushed. This variable would be sent to the TH and TL registers of the DS1621 to configure the desired temperature. The programmable hysteresis was utilized by setting the TH and TL registers higher and lower by 1 respectively. LEDs were used to indicate the state of the buttons and the desired temperature was displayed and continuously updated on the bottom line of the LCD module. The TOUT pin of the DS1621 is used to control the mechanical system. TOUT depends on the value of the TH and TL registers as well as the current temperature read by the DS1621. The MCU was programmed to read TOUT and display the status of the pin on an LED. There was also another switch implemented into the system to control the state of the fans in the mechanical system.

When the code for the system was completed on the Keil software, a schematic of the system was created on the Proteus software. The schematic used for the simulation is shown below in Figure 54. The Keil software was linked to the Proteus software and the source code was downloaded onto the virtual AT89C51 MCU. The system was tested by actuating the push buttons to change the desired temperature relative to the temperature read by the DS1621. The temperature read by the DS1621 was also changed and the performance of the system was observed by checking the state of TOUT relative to the desired temperature and the temperature read by the DS1621. The hysteresis was also observed in this process and the system performed as expected.

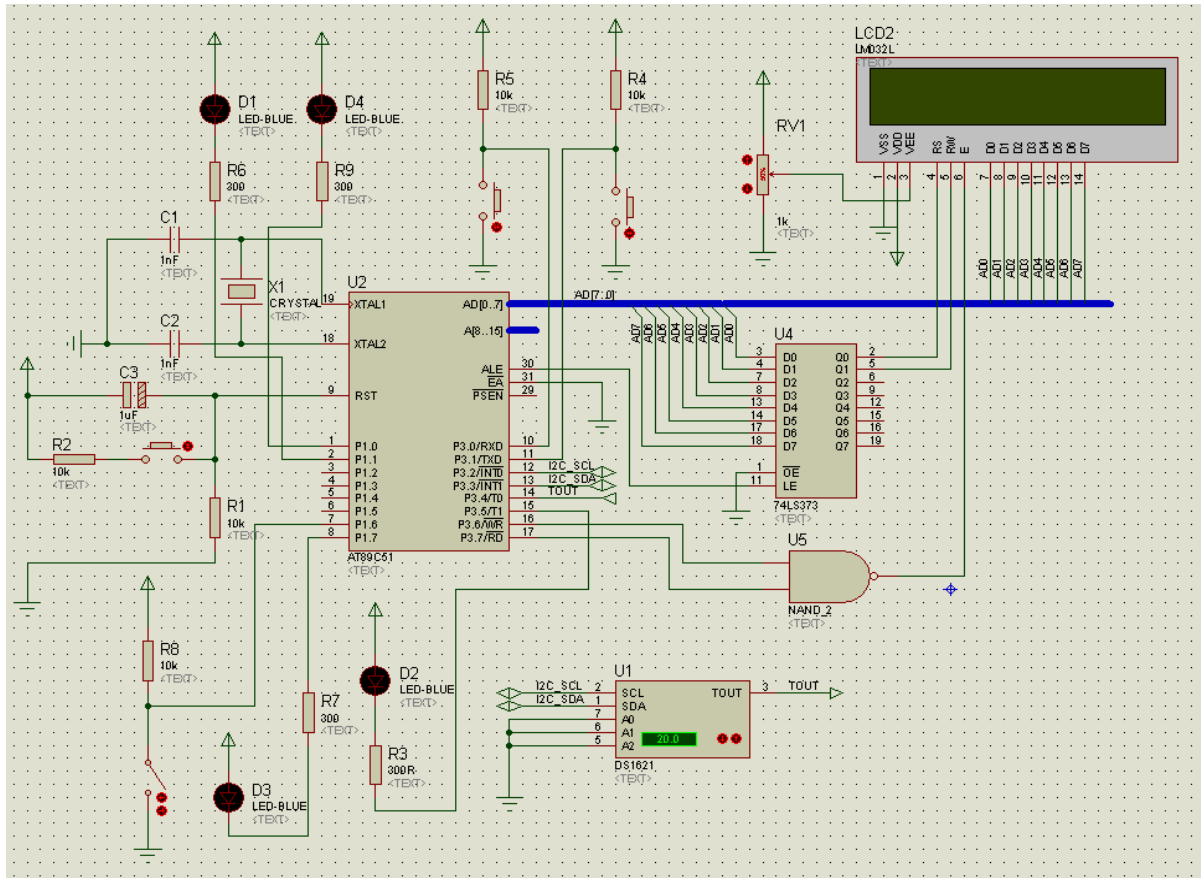


Figure 54: Proteus Schematic of system used for Keil Simulation

The C8051F930 development kit was used for the final implementation of the software. Initially, the Keil software was to be used to program the board. However, it was later found that the Keil software was not compatible with this particular microchip. The solution to this problem was to use the Silicon Labs IDE software instead of Keil to program and debug the development board. The MCU was programmed in 3 modules.

The first module included all of the buttons and switches that were to be used in the user interface. The purpose of this module was to configure the I/O ports and make sure that the MCU could read and write to the ports correctly. This module was tested by simply using LEDs to verify that the MCU was reading and writing the correct states of the buttons and switches.

The second module involved configuring the SMBus on the MCU for the I<sup>2</sup>C serial interface so that the MCU could communicate with the DS1621 digital thermometer. This program involved initializing the DS1621 to read temperature and initialize the TH and TL registers. A while loop was created where the TH and TL registers were continuously updated according to a variable that could be incremented or decremented by momentary push buttons. The TOUT pin from the DS1621 was read by the MCU and the state of TOUT was observed using an LED. The program was tested by initializing the TH and TL registers from within the program. By setting TH and TL above and below the actual room temperature, the initial state of TOUT could be observed. The desired temperature could be incremented and decremented using the push buttons. To make sure the TH and TL registers were updating properly, the push buttons were continuously

pressed until the TOUT LED would switch on or off. The system performed as expected for this test.

The third and final module included the 2-digit 7-segment LED display. The purpose of this component was to display both the user's desired temperature and the current temperature of the conditioned space. This component was also necessary to further test the DSD1621 digital thermometer by allowing the measured temperature and the temperature set in the TH and TL registers to be displayed. The initial program involved converting a hex number to a 2-digit decimal number and displaying it on the 7-segment LED. Once this was accomplished, the program was altered to increment and decrement the 2-digit decimal number based on the inputs from two momentary push buttons.

After the final module code was written and the program was successfully tested, the 3 modules were combined into one program which would provide control for the entire system. The push buttons were used to increment and decrement the desired temperature which was displayed on the 2-digit 7-segment LED. The temperature read by the DS1621 was also read by the MCU and displayed on the 2-digit 7-segment LED. Since only one of these temperatures could be displayed at a time, a switch was incorporated into the program to switch between the desired temperature and the temperature of the conditioned space. A fan switch was also implemented which would take priority over the state of TOUT. When this fan switch was on, the pumps in the system would turn off and the fans would remain on. This final program was tested by building the entire control circuit on a breadboard and making all of the necessary connections to the development board. The system was tested setting all possible input combinations and observing the outputs. The inputs which control the system included TOUT, the fan switch, and the power switch. The outputs were the 2 pump relays and the fan relay. The outputs were measured by observing whether or not the relays were actuated. The logic table that was followed for this testing is shown below in Table 2.

Table 2: Logic Table followed for breadboard testing of control system

Inputs			Outputs		
Power	Fan Switch	TOUT	Fan	Pump 1	Pump 2
0	x	x	0	0	0
1	1	x	1	0	0
1	0	1	1	1	1
1	0	0	0	1	1

### DC-DC converters

The testing of the DC-DC converters was split apart in three sections. First the 12 V to 5V convertor was tested. It was found that in order to achieve the correct output that the  $-V_{out}$  pin that was originally connected to ground needed to remain unconnected. After this problem was resolved, a small load was connected to the convertor and the input was varied within its accepted input range. The 5 Volt to 3.3 Volt convertor was then tested in the same manner, the circuits can be seen in Figure 55 and Figure 56. The convertors were then tested in series converting 12 V to 5V to 3.3V, as seen in Figure 57. The results can be seen in Table 3.

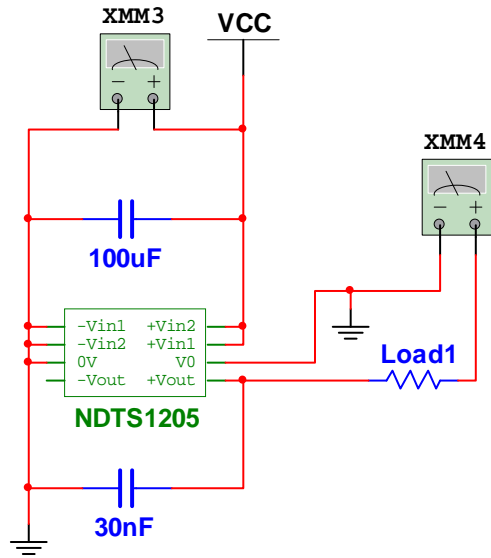


Figure 55: Testing 12 V to 5V Converter

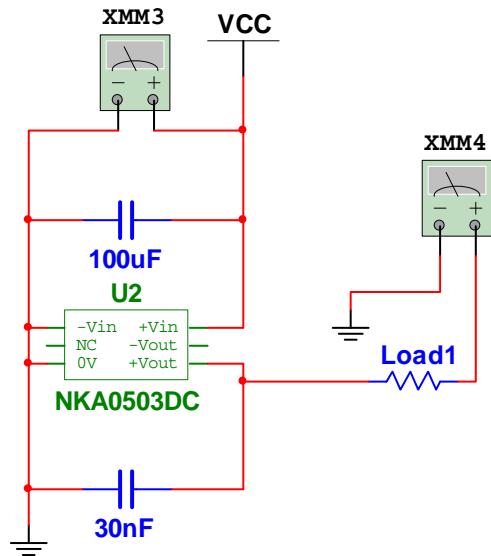


Figure 56: Testing 5 V to 3.3 V Converter



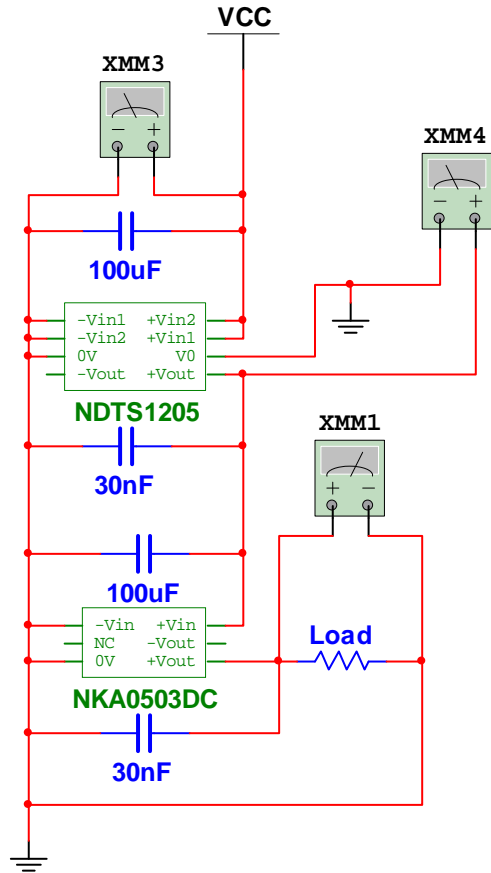


Figure 57: Testing 12 V to 5V to 3.3 V

Table 3: Results from DC-DC Converter Testing

12V to 5V		5V to 3.3V		12V tot 5V to 3.3V		
Input (V)	Output (V)	Input (V)	Output (V)	Input (V)	Output (V)	Output (V)
16	4.98	5.4	3.6	16	4.97	3.337
14	4.98	5.2	3.447	14	4.97	3.335
12	4.98	5.0	3.301	12	4.97	3.333
10	4.98	4.8	3.184	10	4.97	3.337
8	4.98	4.6	3.038	8	4.97	3.337

### Solar Panel, Regulator, and Batteries

On a clear sunny day the solar panel was tested. The open circuit voltage was measured to be 22.3V; the expected value from the datasheet is 21.7V. The solar panel was then connected to the regulator which was connected to the batteries. One pump was connected to the batteries and was run while the voltage on the batteries was monitored. It was seen that the voltage on the batteries was increasing slowly, approximately 0.01V every 5 min. Further tests with the solar panel where planned but due to time constraints these tests were not run.

## Detailed Testing Process

1. Hook solar collector up to the heat source loop if being used. Make sure heat source valves are turned correctly (With solar collector: Close thru valve and open inlet and outlet valves to solar collector. Without solar collector: Open thru valve and close valves for the inlet and outlet of the solar collector.)
2. Fill the water tank up to about 1 inch from the top. Keep extra water on hand, once pump is turned on more will need to be added to the water tank if the solar collector is used.
3. Plug the immersion heater into the wall. Make sure the dial on the heater is turned on to 210°F.
4. Hook up the tap water source to the cold water loop. There is only one inlet to the cold water loop.
5. Turn on the tap water and adjust flow rate to 2.38 gpm for the condenser and 0.53 gpm for the absorber heat exchanger using a graduated cylinder and stopwatch. The flow rate can be changed using the valves within the cold water loop.
6. Turn on the heater in enclosed space and make sure the window is closed. If the duct work from the air conditioner is not attached to the duct work on the side of the space, attach the ductwork.
7. Plug the thermocouples into the thermocouple selector and digital read out.
8. Turn the switch on for the pumps and the fans. As previously mentioned, if the solar collector is connected in the heat source loop, watch the level of the water in the water tank. More water may need to be added to the water tank to ensure that the pump does not run dry. Try to keep at least 3/4 of the tank full.
9. Adjust the hand expansion valve so that a 2 bar (29 psi) pressure drop is created between the two pressure gauges.
10. Wait for the system to reach steady state.
11. Once steady state is achieved, record the temperatures, pressures, and flow rates using the thermocouples, pressure gauges and flow meters integrated into the system.
12. Input the data obtained into the test EES program, EES program is shown below.
13. Turn off the system, unplug the immersion heater, turn off the water supplies water, disconnect water and solar collector, and the drain water tank.

### EES Test Program

```
Q_cond=m_dot_r*(h_2-h_4)
h_2=enthalpy(ammonia_mh, T=T_2, P=P_high)
h_4=enthalpy(ammonia_mh, P=P_high, x=0)
```

```

Q_evap=m_dot_r*(h_6-h_5)
h_5=h_4
h_6=enthalpy(ammonia_mh, T=T_6, x=1)

delta_P=P_high-P_low

epsilon_GA_HE=((T_3-T_9)/(T_3-T_8))

m_dot_str*(h_3-h_9)=Q_GA_HE
call NH3H2O(123,T_9, P_high,c_str : T9,P_9, x_9, h_9,s_9,u_9,v_9,q_9)
call NH3H2O(123,T_3, P_high,c_str : T3,P_3, x_3, h_3,s_3,u_3,v_3,q_3)

Q_abs_HE=m_dot_str*(h_9-h_10)
h_10=h_11
call NH3H2O(123,T_11, P_low,c_str : T11,P_11, x_11, h_11,s_11,u_11,v_11,q_11)

-Q_gen=m_dot_wk*h_1-m_dot_str*h_3-m_dot_r*h_2
call NH3H2O(123,T_1, P_high,c_wk : T1,P_1, x_1, h_1,s_1,u_1,v_1,q_1)
m_dot_wk=m_dot_str+m_dot_r

T_1=converttemp(F,K, T1_test)
T_2=converttemp(F,K, T2_test)
T_3=converttemp(F,K, T3_test)
T_6=converttemp(F,K, T6_test)
T_8=converttemp(F,K, T8_test)
T_9=converttemp(F,K, T9_test)
T_11=converttemp(F,K, T11_test)

(P_high_test+14.7)=P_high*convert(bar, psi)
(P_low_test+14.7)=P_low*convert(bar, psi)

v_dot_str=(m_dot_str*60/872.76)/0.003785412
v_dot_wk=(m_dot_wk*60/872.76)/0.003785412

```

## Testing Results

### Mechanical

In testing, steps 1-8 were followed. When the pump and fan were switched on, the ammonia pump did not turn on. To remedy this, the pressure in the system was reduced until the pump turned on (60 psi). As the system was running, the generator would fill with solution but was not draining quick enough to keep up. This caused the pressure within the generator to increase and the ammonia pump in turn would cut out.

The increase in the temperature and the increase in the pump head were suspected to be the reason for the pump to cut out. Because the generator was not draining fast enough, it would fill

with liquid and run over into the condenser. The cold water flow rate was increased to lower the temperature within the absorber to help cool down the pump.

Due to the generator overflowing into the condenser, steady state could not be reached. In order to show how the system functions in its current state, data was taken at 5 minute intervals over the span of half an hour. The data can be seen in Table 4. Figure 58 shows the temperature versus time from the data in Table 4.

Table 4: Data Collected in Mechanical Test

	Units	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
Time	min	0	5	10	15	20	25	30
T_1	°F	123.5	118.1	112	107.4	103.6	101	98
T_2	°F	136	128	121	115.1	112.1	107.7	104.2
T_3	°F	145	138.3	130.5	124.8	119	115.4	112.3
T_4	°F	56.8	56.3	55.6	56	55.5	55.3	54.6
T_5	°F	63.4	61.5	59.5	59.1	58.1	57.6	56.6
T_6	°F	79.1	76.5	75.3	74.8	74.1	74.3	73.3
T_12	°F	53	53	52.4	52.4	52.4	51.9	51.6
T_13	°F	53.4	56.3	53.8	52.8	54.5	54	53.2
T_14	°F	182.7	175.1	166.4	159.6	154	149.9	145.9
T_15	°F	177.6	169.4	160.4	153.2	147	142.2	137.4
T_17	°F	98.1	94.4	90.3	87.6	85.2	83.3	81.6
T_18	°F	81	86.4	77.8	86.5	81	77	84.3
m_cool_c	gpm	2.38	2.38	2.38	2.38	2.38	2.38	2.38
m_cool_a	gpm	0.53	0.53	0.53	0.53	0.53	0.53	0.53
m_hot	gpm	1.43	1.43	1.43	1.43	1.43	1.43	1.43
m_wk	gpm	0.9	0.9	0.9	0.9	0.9	0.9	0.9
m_str	gpm	1	1	1	1	1	1	1
P_high	psi	72	72	72	72	72	72	72
P_low	psi	62	62	62	62	62	62	62

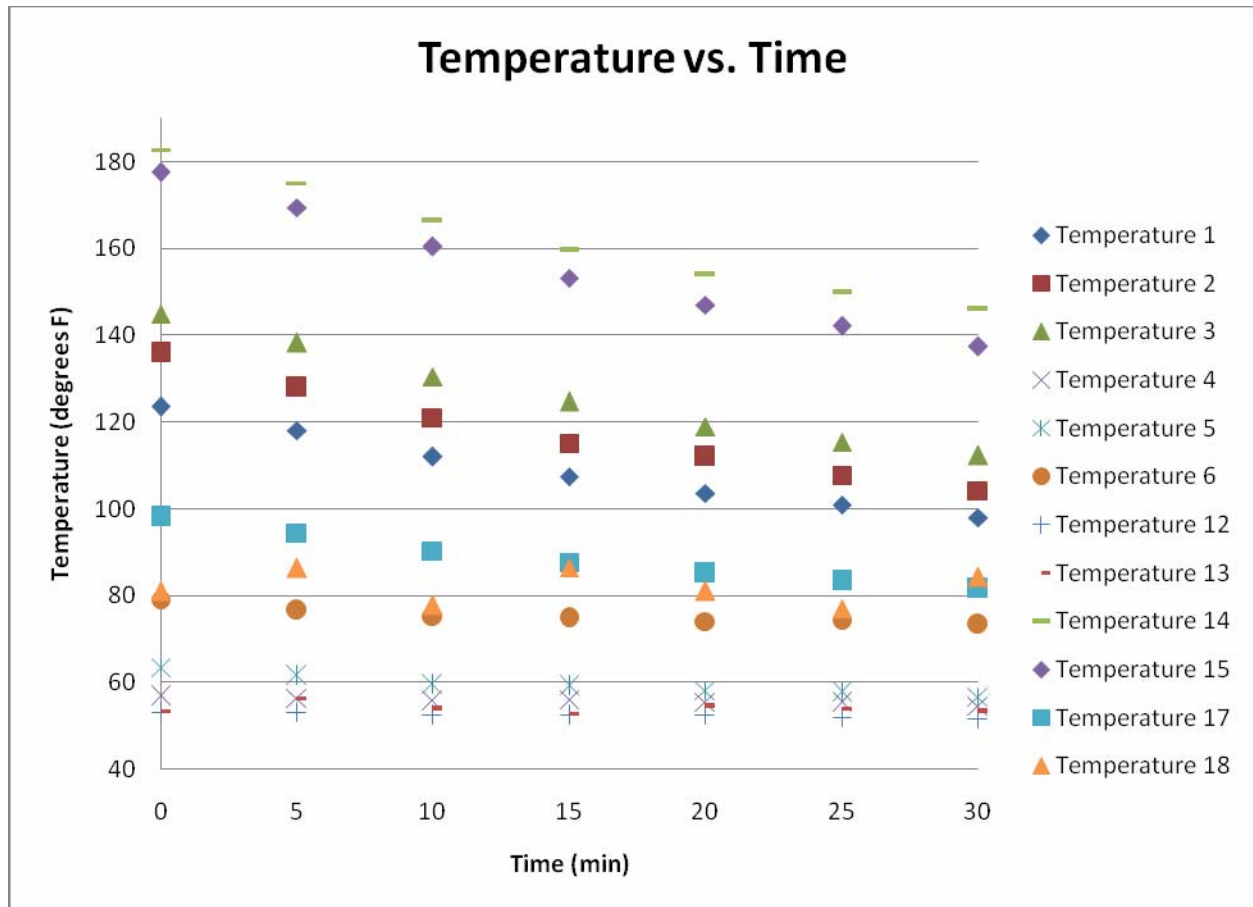


Figure 58: Temperature vs. Time for Mechanical Test

The data collected did not match the expected results from the EES model. The temperature at state point 2, the connecting pipe between the generator and the condenser, was much higher than expected. The expected temperature at this state point was 67.6°F while the temperatures obtained over the hour ranged from 104.2°F to 136°F. The assumption initially made was that the fluid entering the condenser was a saturated ammonia vapor at the high pressure. The temperatures collected during testing contradict this assumption. This is due to the lower pressure of the system and due to the fact that the generator is overflowing. To confirm this, the energy balance was calculated for both the cold water loop and the ammonia side for reading 7.

$$Q_{\text{cond,water}} = \dot{m}_{\text{cool}} C_p (T_{12} - T_{11})$$

$$Q_{\text{cond,water}} = 0.56 \text{ kW}$$

$$\frac{Q_{\text{cond,NH}_3}}{\text{H}_2\text{O}} = \dot{m}_T (h_{18} - h_{12})$$

$$\frac{Q_{\text{cond,NH}_3}}{\text{H}_2\text{O}} = 0.49 \text{ kW}$$

From these calculations it is clear that the fluid flowing through the condenser is the liquid, ammonia/water mixture. More refinement of the thermal compressor portion of the system is needed, specifically the generator.

### Electrical

The final testing of the system was performed in a similar way to the final breadboard testing. The pumps and fans were connected to the connector from the circuit box as well as the 6V batteries and temperature sensor. A thermocouple was placed near the DS1621 inside the conditioned space to confirm the temperature readings from the sensor. By running the system and changing the desired temperature, the state of TOUT could be observed by whether or not the fans were running. When the desired temperature fell to 1°C below the temperature in the conditioned space, the fans would switch on. When the temperature rose to 1°C above the temperature in the conditioned space, the fans would switch off. The fan switch was also tested. When the fan switch was switched on, the pumps in the system turned off and the fans turned on. When the fan switch was switched off, the pumps turned off and the fan turned on or off depending on the desired temperature. Unfortunately, the mechanical system was not functioning properly, so no further testing involving the cooling of the conditioned space could be performed. However, the control system performed adequately and accomplished the goals set in the initial design.

### Complete System

Because the mechanical system was not functioning properly, the two components, electrical and mechanical, were not tested together.

### **Section III: Evaluation and Recommendations**

## Mechanical

The main cause of the system not functioning properly is that there is too much head loss inside of the generator. This does not allow the generator to drain at an adequate flow rate. The two main sources of head loss in the generator are the flow around the coils as well as the exit of the generator. The solution to this problem must be found experimentally due to the lack of data on the head loss coefficients of the generator components. Below is a list of experiments that must be run in order to incorporate these changes in geometry.

- Increase clearance around coils and baffle in the generator
- Increase outlet port diameter of the generator

The ammonia pump is also an area where more improvement is needed. After it was determined that the pump was unable to operate at the desired inlet pressure (69 psig), it was decided that a different pump is required to operate at the conditions originally designed. These conditions are as follows:

- Inlet Pressure: 69 psig
- Outlet Pressure: 93 psig
- Temperature: 64 C
- Flow Rate @ 60 psi of head: 1.8 gpm

## Electrical

There are some changes to the design that would improve the system. The system could be more user friendly by adding the LCD module that the design originally called for. The LCD would be able to display multiple temperatures simultaneously and would allow for a more sophisticated system. The LCD could display the current status of the system and various temperatures throughout the system.

Due to time constraints, the testing of the temperature sensor and solar panel may be inadequate. The data obtained from testing the temperature sensor with a thermocouple only consisted of a few values.

Further testing of the temperature sensor is recommended to make sure the sensor is reading the temperature accurately. The solar panel should also undergo more testing. The test that was run on the solar panel was a conceptual test and to ensure that the components were working properly. Due to the recent weather conditions, the solar panel has not been tested thoroughly enough to determine how long it would take to charge the batteries. However, given the right conditions, the solar panel will be able to charge the batteries without an external charger.

The system would also benefit from replacing the 2 AAA batteries on the development board with identical rechargeable batteries. These rechargeable batteries would allow continuous use of the system as they could be recharged from the 3.3V output on the PCB. This would also



allow in-system debugging of the development board without having to hook up a 12 volt supply or using a wall outlet.

### Cost Analysis

The budget for the Solar Cooling Demonstration Unit was \$5000.00. As was expected from our cost estimate and analysis from semester 1, the budget was not met. Not meeting the budget is mostly due to parts that were overlooked in the estimate, such as bolts, wood for solar mounts, and Yor-Lock fittings. Another factor that caused the budget to be missed was the diaphragm melting in the heat source loop pump. A second pump, circulator pump, had to be purchased to replace this pump. The final cost of the project can be seen in Table 5.

Table 5: Cost of Project

Component	Total
Condenser	508
Generator/ absorber heat exchanger	399
Absorber heat exchanger	296
Casters, Tubing	236.47
Batteries	200
Solar collector	860
Evaporator	989
Immersion Heater	287.43
Pumps for absorber/generator and solar collector	222.99
Pressure Gages, Flowmeters, Misc. Fittings	238
Circular Pump	118
Solar Panel, Charge Controller	552.01
DC converters, Fans, Microcontroller	94.1
Misc. Electrical	150
Misc. Mechanical (wood, bolts)	548
Total	5699

## **Conclusion**

With these changes incorporated, the thermal compressor portion of the system would function as designed. The generator would not fill with ammonia/water mixture and the generator could be tested for its' effectiveness at separating the ammonia from solution. This would allow for a fully-functional test of the entire mechanical system.

The general concept that the solar panel would be able to charge the batteries was confirmed. The length of time that it will need to charge the batteries is unknown but, under sunny conditions, the solar panel was capable of keeping up with one pump running. Given that the batteries have a capacity of 200 Amp-hours and that the system only needs 96 Amp-hours to run for 4 hours, the system has enough power to run continuously for the desired amount of time given in the problem statement. If the solar panel is used to charge the batteries in between uses, the system should not have to use another power source other than the sun.

The control of the system is also adequate. The desired temperature can be changed by the user and this temperature can be observed along with the temperature of the space. Using the temperature sensor, the system is able to turn the fans on and off accordingly.

## Appendix A

### EES program with solution

```
subprogram gen(T_1, T_3, T_14, T_15, Q_gen, c_str, m_dot_hot, m_dot_wk, P_high, v_3, epsilon_gen)
  "Inputing properties of tubing"
  D_o=.5*.0254
  D_i=D_o-.035*.0254
  coil_OD=5.75*.0254
  gen_OD=6.5
  gen_ID=5
  k_steel=51.9/1000

  "Thermal Properties of Ammonia/Water"
  mu_water=Viscosity(Steam,T=T_3,P=P_high)
  mu_ammonia=Viscosity(Ammonia_mh,T=T_3,P=P_high)
  mu_cool=mu_ammonia*c_str+mu_water*(1-c_str)

  cp_water=SpecHeat(Steam,T=T_3,P=P_high)
  cp_ammonia=SpecHeat(Ammonia_mh,T=T_3,P=P_high)
  cp_cool=cp_ammonia*c_str+cp_water*(1-c_str)

  v_water=Volume(Steam,T=T_3,P=P_high)
  v_ammonia=Volume(Ammonia_mh,T=T_3,P=P_high)
  v_cool=v_ammonia*c_str+v_water*(1-c_str)

  k_water=Conductivity(Steam,T=T_3,P=P_high)/1000
  k_ammonia=Conductivity(Ammonia_mh,T=T_3,P=P_high)/1000
  k_cool=k_ammonia*c_str+k_water*(1-c_str)

  Pr_cool=cp_cool*mu_cool/k_cool

  "finding properties of 25% Ethylene Glycol/Water mixture"
  CALL BRINEPROP2('EG', 25, T_m-273.15: FP_slr, rho_m, Cp_hot, k_h, nu_hot, Pr_hot)
  k_hot=k_h/1000
  mu_hot=nu_hot*rho_m/1000

  "Calculating the Log-Mean Temperature Difference"
  delta_T_1=T_14-T_1
  delta_T_2=T_15-T_3
  delta_T_lm=(-delta_T_2+delta_T_1)/ZZ
  ZZ=ln(delta_T_1/delta_T_2)
  T_m=(T_14+T_15)/2
  Q_gen=UA*delta_T_lm

  "Convective heat transfer coefficient inside the tubing"
  u_i=m_dot_hot/(rho_m*3.14*(D_i^2)/4)
  Re_D_i=u_i*D_i*rho_m/mu_hot
  Nu_D_i=.023*Re_D_i^(4/5)*Pr_hot^.3
  h_i=Nu_D_i*k_hot/D_i

  "Dummy variable used to prevent errors"
  "Average temperature of water from solar collector"
  "Finding needed UA"
  "Liquid Velocity"
  "Reynolds number of the flow"
  "Nusselt number of the flow"
  "heat transfer coefficient"
```

"Convective heat transfer coefficient outside the tubing"

$v_{wk} = m_{dot\_wk} \cdot v_3 / (((gen\_OD \cdot 0.0254)^2 - (gen\_ID \cdot 0.0254)^2) \cdot 3.14 / 4 - (3.14 \cdot coil\_OD \cdot D_o))$

"Liquid Velocity"

$Re\_Do = v_{wk} \cdot D_o / (v_3 \cdot \mu_{cool})$

"Reynolds number of the flow"

$Nuu\_D_o = C \cdot Re\_Do^m \cdot Pr_{cool}^{(1/3)}$

"Nusselt number of the flow"

$m = 0.466$

$C = 0.683$

$h_o = Nuu\_D_o \cdot k_{cool} / D_o$

"heat transfer coefficient"

"Energy Balance"

$Q_{gen} = L_{gntr} \cdot h_i \cdot 3.14 \cdot D_i \cdot (T_m - T_i)$

$Q_{gen} = L_{gntr} \cdot h_o \cdot 3.14 \cdot D_o \cdot (T_o - T_3)$

"Finding needed Length of tubing"

$1/UA = 1/(h_i \cdot 3.14 \cdot D_i \cdot L_{gntr}) + \ln(D_o/D_i)/(2 \cdot 3.14 \cdot k_{steel} \cdot L_{gntr}) + 1/(h_o \cdot 3.14 \cdot D_o \cdot L_{gntr}) + 0.0002/(3.14 \cdot D_i \cdot L_{gntr}) + 0.0002/(3.14 \cdot D_o \cdot L_{gntr})$

"effectiveness using effectiveness-NTU relationship"

$C_{max} = m_{dot\_hot} \cdot cp_{hot}$

$C_{min} = m_{dot\_wk} \cdot cp_{cool}$

$C_r = C_{min} / C_{max}$

$\epsilon_{gen} = 2 / (1 + C_r + ((1 + C_r^2)^{0.5}) \cdot (1 + \exp(-NTU \cdot (1 + C_r^2)^{0.5}))) / (1 - \exp(-NTU \cdot (1 + C_r^2)^{0.5})))$

$NTU = UA / (C_{min})$

$coils = (L_{gntr}) / (((coil\_OD - (D_o/2)) \cdot 3.14)$

end

"-----"

"

Inputs

"-----"

$Q_{evap} = 1.5$  {Cooling Capacity}

$\Delta P = 2$  {Pressure Drop}

$T_6 = 8 + 273.15$  {Evaporator Temperatures}

$T_{12} = 284$  {Water Loop Inputs}

$T_{16} = 284$

$T_2 = T_{2\_s} + T_{sh}$

$T_{sh} = 3$

$m_{dot\_hot} = 0.5$

$m_{dot\_cool\_c} = 0.15$

$m_{dot\_wk} = 0.08$

$\epsilon_{abs\_he} = 0.5$  {Heat Exchanger Effectiveness}

$\epsilon_{ga\_he} = 0.5$

{ $\epsilon_{gen} = 0.5$ }

$q_7 = 0$  {Assumptions}

$q_3 = 0$

$q_1 = -0.001$

call gen( $T_1, T_3, T_{14}, T_{15}, Q_{gen}, c_{str}, m_{dot\_hot}, m_{dot\_wk}, P_{high}, v_3, \epsilon_{gen}$ )

```

"-----"
"
"                                     Water Loop Properties
"-----"
h_16=enthalpy(steam, T=T_16, x=0)
h_17=enthalpy(steam, T=T_17, x=0)

epsilon_abs_HE=(T_17-T_16)/(T_9-T_16)           {Effectiveness of Absorber}
Q_abs_HE=m_dot_cool_a*(h_17-h_16)

Q_cond=m_dot_cool_c*(h_13-h_12)
h_12=enthalpy(steam, T=T_12, x=0)               {Specific Enthalpy}
h_13=enthalpy(steam, T=T_13, x=0)

Q_gen=m_dot_hot*(h_14-h_15)                     {Energy Balance}
epsilon_gen=(m_dot_hot*(T_14-T_15))/C1          {Effectiveness of Generator}
C1=m_dot_str*(T_14-T_1)
h_14=enthalpy(steam, T=T_14, x=0)
h_15=enthalpy(steam, T=T_15, x=0)

"-----"
"
"                                     Generator
"-----"
-Q_gen=m_dot_wk*h_1-m_dot_str*h_3-m_dot_r*h_2    {Energy Balance}

m_dot_wk=m_dot_str+m_dot_r                       {Continuity}
m_dot_str*c_str+m_dot_r=m_dot_wk*c_wk

call NH3H2O(238,P_high,c_wk,q_1:T_1,P_1,x_1,h_1,s_1,u_1,v_1,q1)   {Property Calls}
call NH3H2O(128,T_3,P_high,q_3:T3,P_3,c_str,h_3,s_3,u_3,v_3,q3)
call NH3H2O(248,P_high,h_2,l:T_1e,P_1e,x_1e,h_1e,s_1e,u_1e,v_1e,q_1e)
T_1e=T_3

"-----"
"
"                                     Absorber
"-----"
m_dot_r*h_6+m_dot_str*h_11-m_dot_wk*h_7=0        {Energy Balance}

h_10=h_11                                         {Throttling}

call NH3H2O(238,P_low,c_wk,q_7:T_7,P_7,x_7,h_7,s_7,u_7,v_7,q7)   {Property Calls}

call NH3H2O(234,P_high,c_str,h_10:T10,P_10,x_10,h10,s_10,u_10,v_10,q_10)
call NH3H2O(234,P_low,c_str, h_11:T11,P_11,x_11,h11,s_11,u_11,v_11,q_11)

"-----"
"
"                                     Heat Exchanger - Absorber
"-----"
Q_abs_HE=m_dot_str*(h_9-h_10)                    {Energy Balance}

"-----"
"
"                                     Heat Exchanger - Generator/Absorber

```

```

"-----"
m_dot_str*(h_3-h_9)=Q_GA_HE {Energy Balance}
{m_dot_wk*(h_1-h_8)=Q_GA_HE}

epsilon_GA_HE=((T_3-T_9)/(T_3-T_8))

call NH3H2O(234,P_high,c_str,h_9:T_9,P_9,x_9,h9,s_9,u_9,v_9,q_9)

"-----"
"                               Evaporator
"-----"
Q_evap=m_dot_r*(h_6-h_5) {Energy Balance}

delta_P=P_high-P_low {Expansion Valve}
h_5=h_4

T_5=temperature(ammonia_mh, h=h_5, P=P_low) {Evaporator Inlet}

h_6=enthalpy(ammonia_mh, T=T_6, x=1) {Evaporator Outlet}
P_low=pressure(ammonia_mh, T=T_6, h=h_6)

"-----"
"                               Condenser
"-----"
Q_cond=m_dot_r*(h_2-h_4) {Energy Balance}
{Energy Balance}

h_2=enthalpy(ammonia_mh, T=T_2, P=P_high)
T_2_s=T_sat(ammonia_mh,P=P_high)

h_4=enthalpy(ammonia_mh, P=P_high, x=0) {Condenser Output}
T_4=temperature(ammonia_mh, P=P_high, h=h_4)

"-----"
"                               Pump Work
"-----"
W_p=m_dot_wk*(h_8-h_7) {Pump Work}
W_p=m_dot_wk*(v_7)*(delta_P*convert(bar, kPa)/1000)

call NH3H2O(234,P_high,c_wk,h_8:T_8,P_8,x_8,h8,s_8,u_8,v_8,q8) {Property Call}

```

Parametric Table

	1	2	3	4	5	6	7	8	9	10	11
	$c_{str}$	$c_{wk}$	$\dot{m}_r$ [kg/s]	$\dot{m}_{str}$ [kg/s]	$\dot{m}_{wk}$ [kg/s]	$Q_{gen}$ [kW]	$Q_{abs,HE}$ [kW]	$T_{14}$ [K]	$T_{15}$ [K]	$\delta p$ [bar]	$\eta_{gen}$
Run 1	0.3723	0.3891	0.001254	0.04549	0.04674	2.627	2.603	388.4	388	1.5	0.3305
Run 2	0.3727	0.3903	0.001255	0.0436	0.04485	2.625	2.6	390.2	389.8	1.556	0.3299
Run 3	0.3732	0.3915	0.001256	0.04185	0.04311	2.622	2.598	392.1	391.7	1.611	0.3292
Run 4	0.3737	0.3927	0.001257	0.04023	0.04149	2.62	2.595	393.9	393.5	1.667	0.3286
Run 5	0.3741	0.3938	0.001258	0.03873	0.03999	2.618	2.592	395.8	395.4	1.722	0.328
Run 6	0.3746	0.395	0.001259	0.03732	0.03858	2.615	2.59	397.6	397.2	1.778	0.3274
Run 7	0.3751	0.3962	0.00126	0.03601	0.03727	2.613	2.588	399.5	399.1	1.833	0.3268
Run 8	0.3755	0.3974	0.001261	0.03478	0.03604	2.611	2.585	401.4	401	1.889	0.3263
Run 9	0.376	0.3986	0.001262	0.03362	0.03489	2.609	2.583	403.3	402.9	1.944	0.3257
Run 10	0.3764	0.3998	0.001264	0.03253	0.0338	2.608	2.581	405.1	404.7	2	0.3252

## Solution

$C1=1.848$  [kg\*K/s]

$c_{str}=0.3793$

$c_{wk}=0.3891$

$\delta P=2$  [bar]

$\epsilon_{abs\_he}=0.5$

$\epsilon_{ga\_he}=0.5$

$\epsilon_{gen}=0.3405$

$h_{10}=34.68$  [kJ/kg]

$h_{11}=34.68$  [kJ/kg]

$h_8=56.98$  [kJ/kg]

$h_9=87.5$  [kJ/kg]

$h_1=104.1$  [kJ/kg]

$h_{10}=34.68$  [kJ/kg]

$h_{11}=34.68$  [kJ/kg]

$h_{12}=45.55$  [kJ/kg]

$h_{13}=55.68$  [kJ/kg]

$h_{14}=410.5$  [kJ/kg]

$h_{15}=405.2$  [kJ/kg]

$h_{16}=45.55$  [kJ/kg]

$h_{17}=169.4$  [kJ/kg]

$h_{1e}=1470$  [kJ/kg]

$h_2=1470$  [kJ/kg]

$h_3=115.9$  [kJ/kg]

$h_4=260.5$  [kJ/kg]

$h_5=260.5$  [kJ/kg]

$h_6=1454$  [kJ/kg]

$h_7=56.98$  [kJ/kg]

$h_8=56.98$  [kJ/kg]

$h_9=87.5$  [kJ/kg]

$\dot{m}_{cool\_a}=0.03357$

$\dot{m}_{cool\_c}=0.15$

$\dot{m}_{hot}=0.5$  [kg/s]

$\dot{m}_r=0.001257$  [kg/s]

$\dot{m}_{str}=0.07874$  [kg/s]

$\dot{m}_{wk}=0.08$  [kg/s]

$P_1=7.751$  [bar]

$P_{10}=7.751$  [bar]

P\_11=5.751 [bar]  
P\_1e=7.751 [bar]  
P\_3=7.751 [bar]  
P\_7=5.751 [bar]  
P\_8=7.751 [bar]  
P\_9=7.751 [bar]  
P\_high=7.751 [bar]  
P\_low=5.751 [bar]  
q1=-0.001 [%]  
q3=0 [%]  
q7=0 [%]  
q8=-0.001 [%]  
q\_1=-0.001 [%]  
q\_10=-0.001 [%]  
q\_11=-0.001 [%]  
q\_1e=1 [%]  
q\_3=0 [%]  
q\_7=0 [%]  
q\_9=-0.001 [%]  
Q\_abs\_HE=4.159 [kW]  
Q\_cond=1.52 [kW]  
Q\_evap=1.5 [kW]  
Q\_GA\_HE=2.24 [kW]  
Q\_gen=2.653 [kW]  
s\_1=0.9236 [kJ/kg\*K]  
s\_10=0.716 [kJ/kg\*K]  
s\_11=0.7167 [kJ/kg\*K]  
s\_1e=5.003 [kJ/kg\*K]  
s\_3=0.9547 [kJ/kg\*K]  
s\_7=0.7869 [kJ/kg\*K]  
s\_8=0.7863 [kJ/kg\*K]  
s\_9=0.8726 [kJ/kg\*K]  
T10=331.3 [K]  
T11=331.4 [K]  
T3=349.6 [K]  
T\_1=347.7 [K]  
T\_12=284 [K]  
T\_13=286.4 [K]  
T\_14=371.1 [K]  
T\_15=369.9 [K]  
T\_16=284 [K]  
T\_17=313.6 [K]  
T\_1e=349.6 [K]  
T\_2=292.9 [K]  
T\_2\_s=289.9 [K]  
T\_3=349.6 [K]



T\_4=289.9 [K]  
T\_5=281.2 [K]  
T\_6=281.2 [K]  
T\_7=336.8 [K]  
T\_8=336.9 [K]  
T\_9=343.2 [K]  
T\_sh=3 [K]  
u\_1=103.3 [kJ/kg]  
u\_10=33.76 [kJ/kg]  
u\_11=34 [kJ/kg]  
u\_1e=1308 [kJ/kg]  
u\_3=115 [kJ/kg]  
u\_7=56.29 [kJ/kg]  
u\_8=56.05 [kJ/kg]  
u\_9=86.57 [kJ/kg]  
v\_1=0.001008 [m3/kg]  
v\_10=0.001185 [m3/kg]  
v\_11=0.001185 [m3/kg]  
v\_1e=0.209 [m3/kg]  
v\_3=0.001212 [m3/kg]  
v\_7=0.001198 [m3/kg]  
v\_8=0.001198 [m3/kg]  
v\_9=0.001202 [m3/kg]  
W\_p=0.00001916 [kW]  
x\_1=0.3891 [%]  
x\_10=0.3793 [%]  
x\_11=0.3793 [%]  
x\_1e=0.9706 [%]  
x\_7=0.3891 [%]  
x\_8=0.3891 [%]  
x\_9=0.3793 [%]  
C=0.683  
coils=8.806  
coil\_OD=0.1461  
cp\_ammonia=2.468  
cp\_cool=3.537  
Cp\_hot=3.966  
cp\_water=4.19  
C\_max=1.983  
C\_min=0.2829  
C\_r=0.1427  
c\_str=0.3793  
delta\_T\_1=23.47  
delta\_T\_2=20.28  
delta\_T\_lm=21.84  
D\_i=0.01181

D\_o=0.0127  
epsilon\_gen=0.3405  
FP\_slr=-10.98  
gen\_ID=5  
gen\_OD=6.5  
h\_i=13.11  
h\_o=0.85  
k\_ammonia=0.0000319  
k\_cool=0.0004182  
k\_h=0.5213  
k\_hot=0.0005213  
k\_steel=0.0519  
k\_water=0.0006543  
L\_gntr=3.863  
m=0.466  
mu\_ammonia=0.00001216  
mu\_cool=0.000235  
mu\_hot=0.0007604  
mu\_water=0.0003711  
m\_dot\_hot=0.5 [kg/s]  
m\_dot\_wk=0.08 [kg/s]  
NTU=0.4294  
Nuu\_D\_i=296.9  
Nuu\_D\_o=25.81  
nu\_hot=0.0007699  
Pr\_cool=1.987  
Pr\_hot=5.857  
P\_high=7.751 [bar]  
Q\_gen=2.653 [kW]  
Re\_Do=1485  
Re\_D\_i=70922  
rho\_m=987.6  
T\_1=347.7 [K]  
T\_14=371.1 [K]  
T\_15=369.9 [K]  
T\_3=349.6 [K]  
T\_i=369.1  
T\_m=370.5  
T\_o=369.8  
UA=0.1215  
u\_i=4.623  
v\_3=0.001212 [m<sup>3</sup>/kg]  
v\_ammonia=0.2102  
v\_cool=0.08037  
v\_water=0.001026  
v\_wk=0.0333

$$ZZ=0.1459$$